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(54) **ELECTRONIC DEVICES WITH TUNABLE LENSES**

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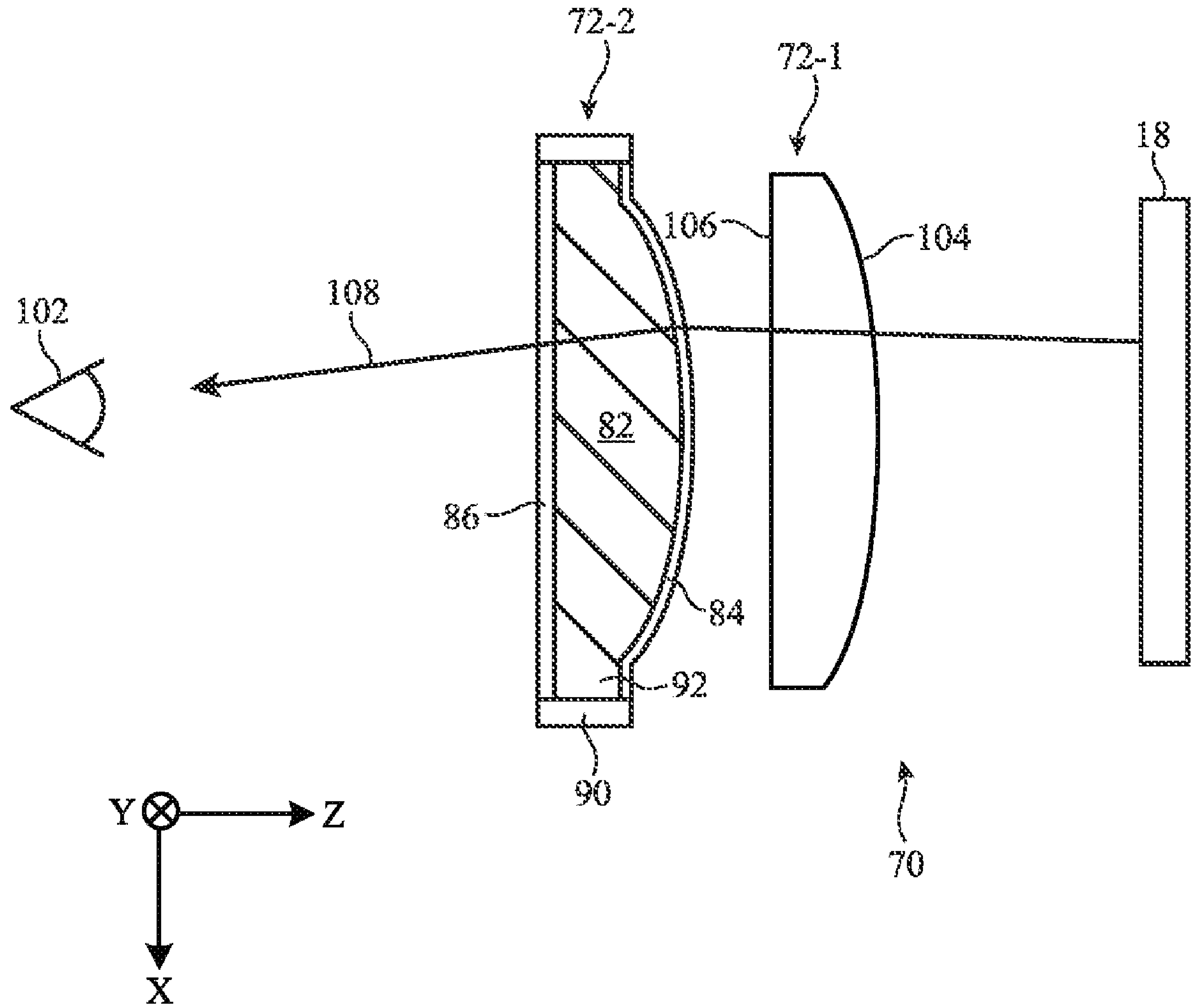
(57) **ABSTRACT**

An electronic device may include an optical module with a display and a tunable lens. During operation, the electronic device may gather data and adjust the tunable lens based on the gathered data. The optical module may include a non-adjustable lens element with convex curvature in addition to the tunable lens. The optical module may include a Fresnel lens element in addition to the tunable lens. The optical module may include a catadioptric lens in addition to the tunable lens. The optical module may include a catadioptric lens that includes the tunable lens. The optical module may have a birdbath architecture that includes the tunable lens. The optical module may include a waveguide and the tunable lens may be an adjustable positive bias lens and/or an adjustable negative bias lens.



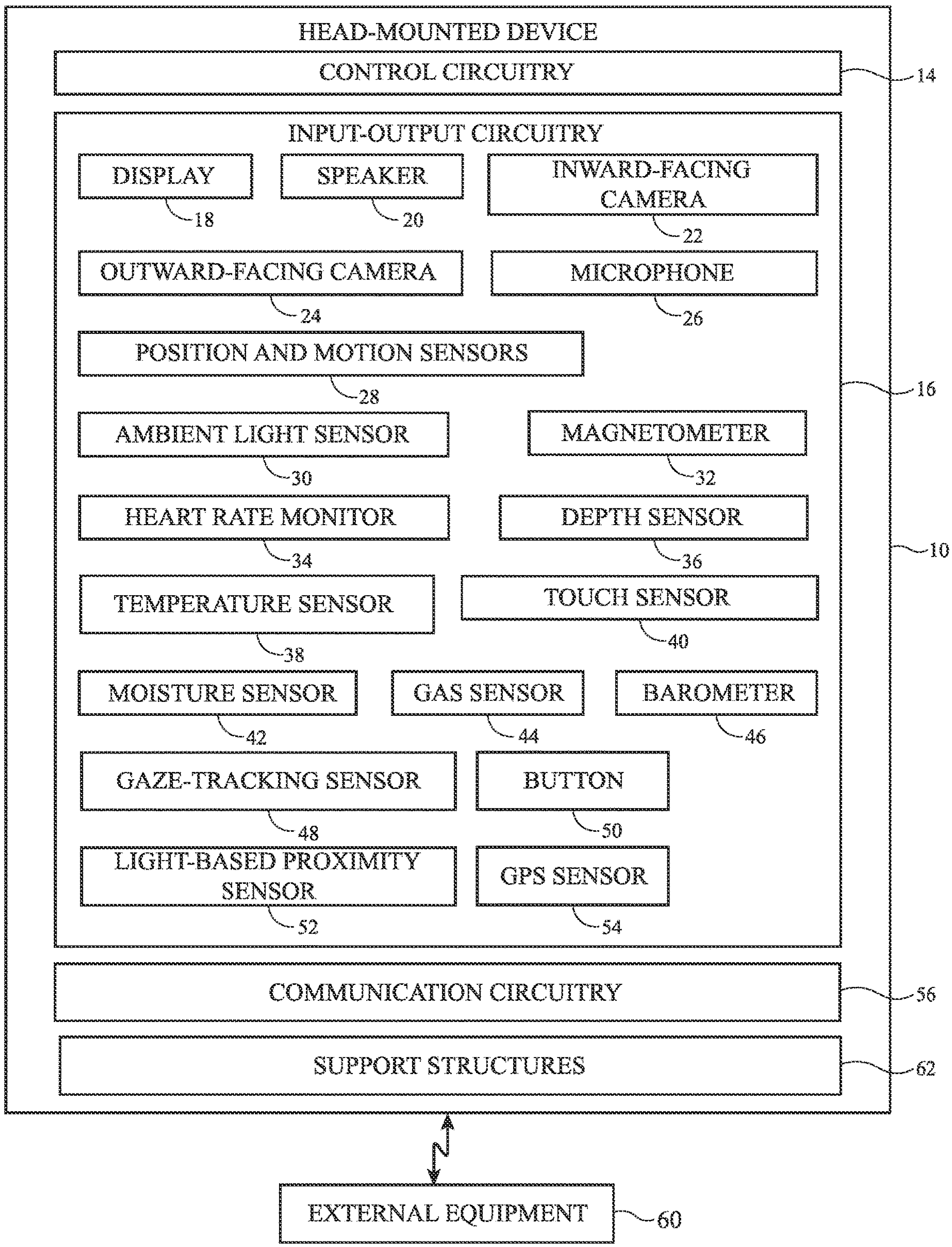

HEAD-MOUNTED DEVICE
CONTROL CIRCUITRY
14
INPUT-OUTPUT CIRCUITRY
DISPLAY
18
SPEAKER
20
INWARD-FACING CAMERA
22
OUTWARD-FACING CAMERA
24
MICROPHONE
26
POSITION AND MOTION SENSORS
28
16
AMBIENT LIGHT SENSOR
30
MAGNETOMETER
32
HEART RATE MONITOR
34
DEPTH SENSOR
36
10
TEMPERATURE SENSOR
38
TOUCH SENSOR
40
MOISTURE SENSOR
42
GAS SENSOR
44
BAROMETER
46
GAZE-TRACKING SENSOR
48
BUTTON
50
LIGHT-BASED PROXIMITY SENSOR
52
GPS SENSOR
54
COMMUNICATION CIRCUITRY
56
SUPPORT STRUCTURES
62
EXTERNAL EQUIPMENT
60

FIG. 1

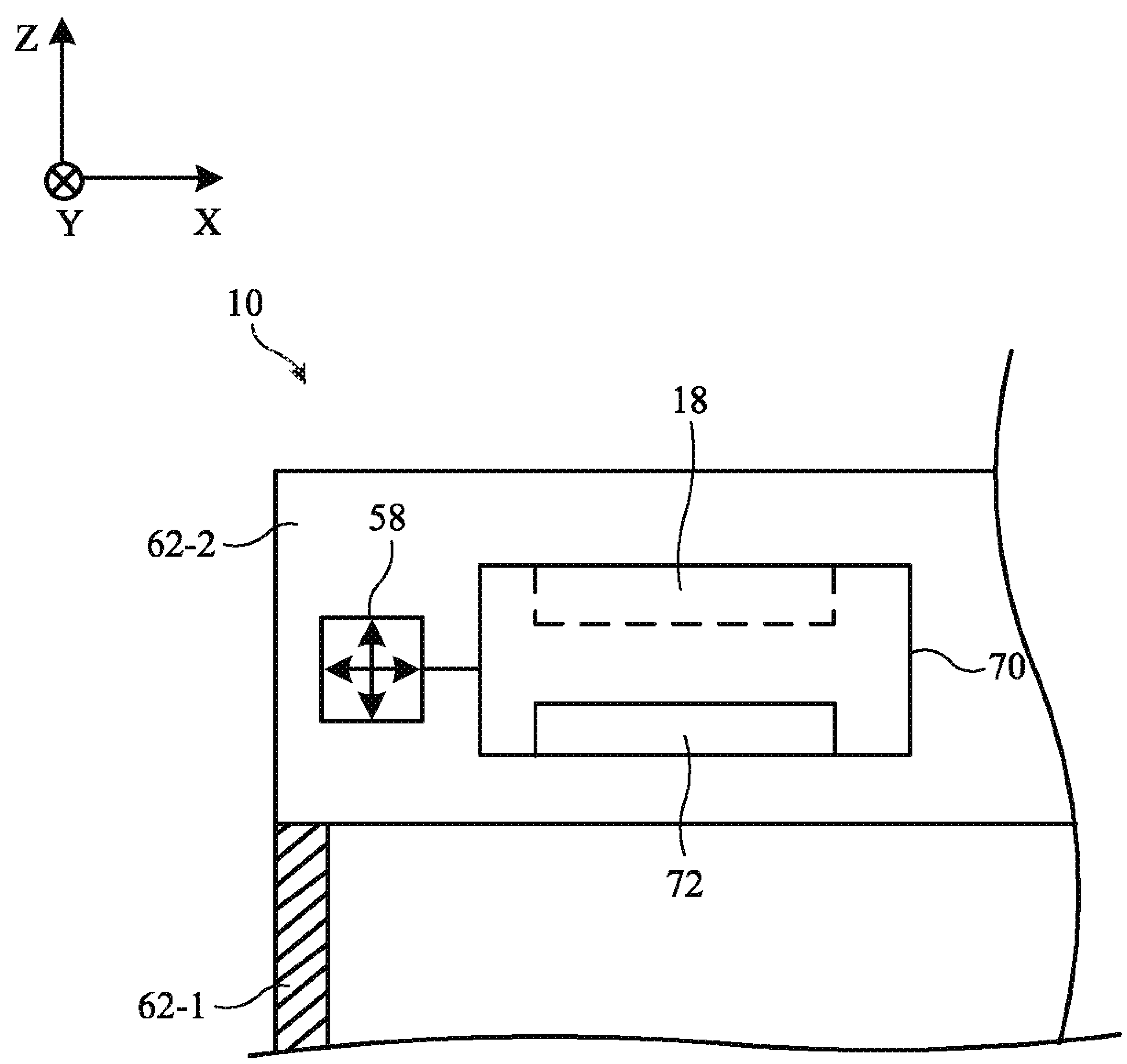


FIG. 2

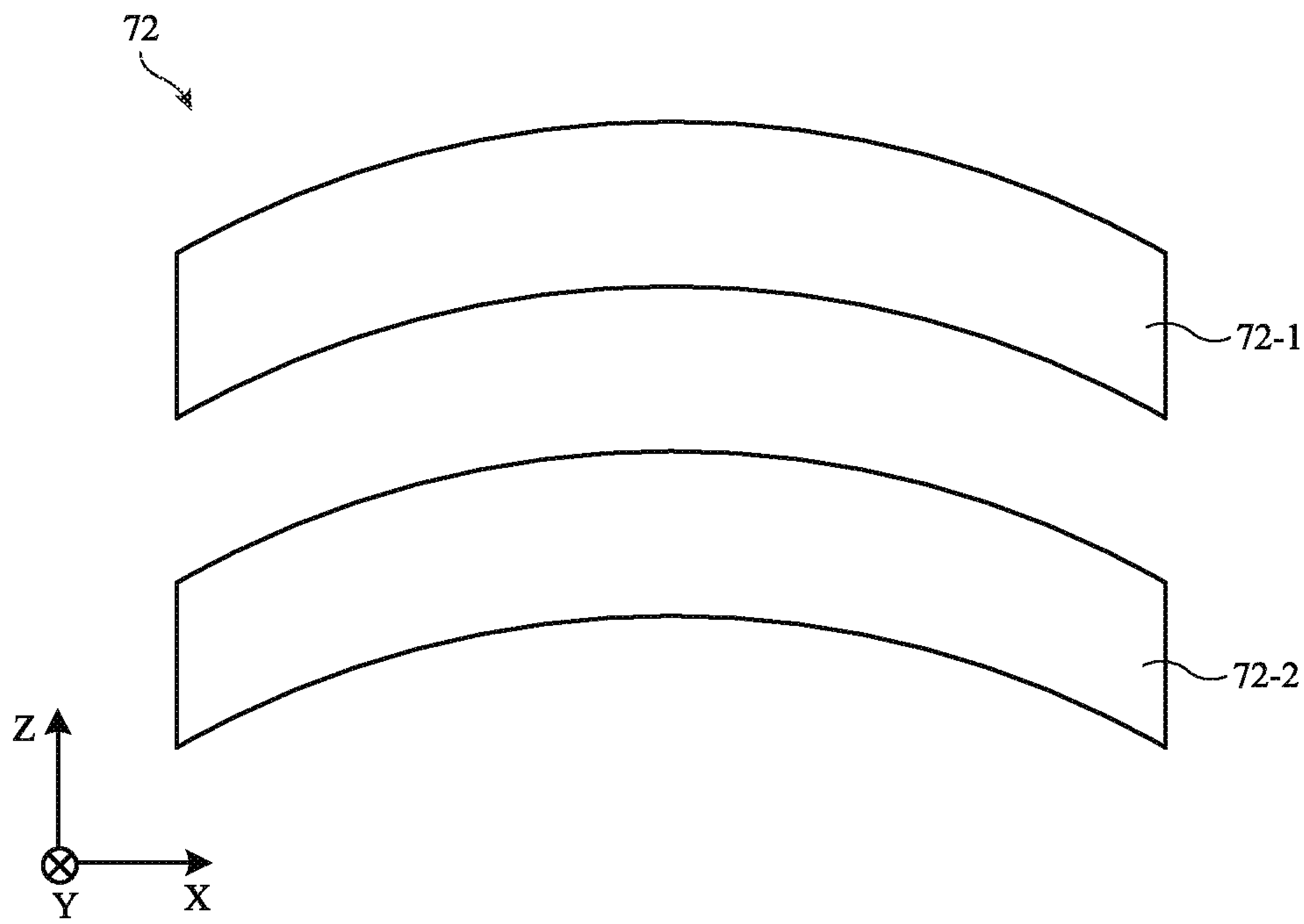


FIG. 3

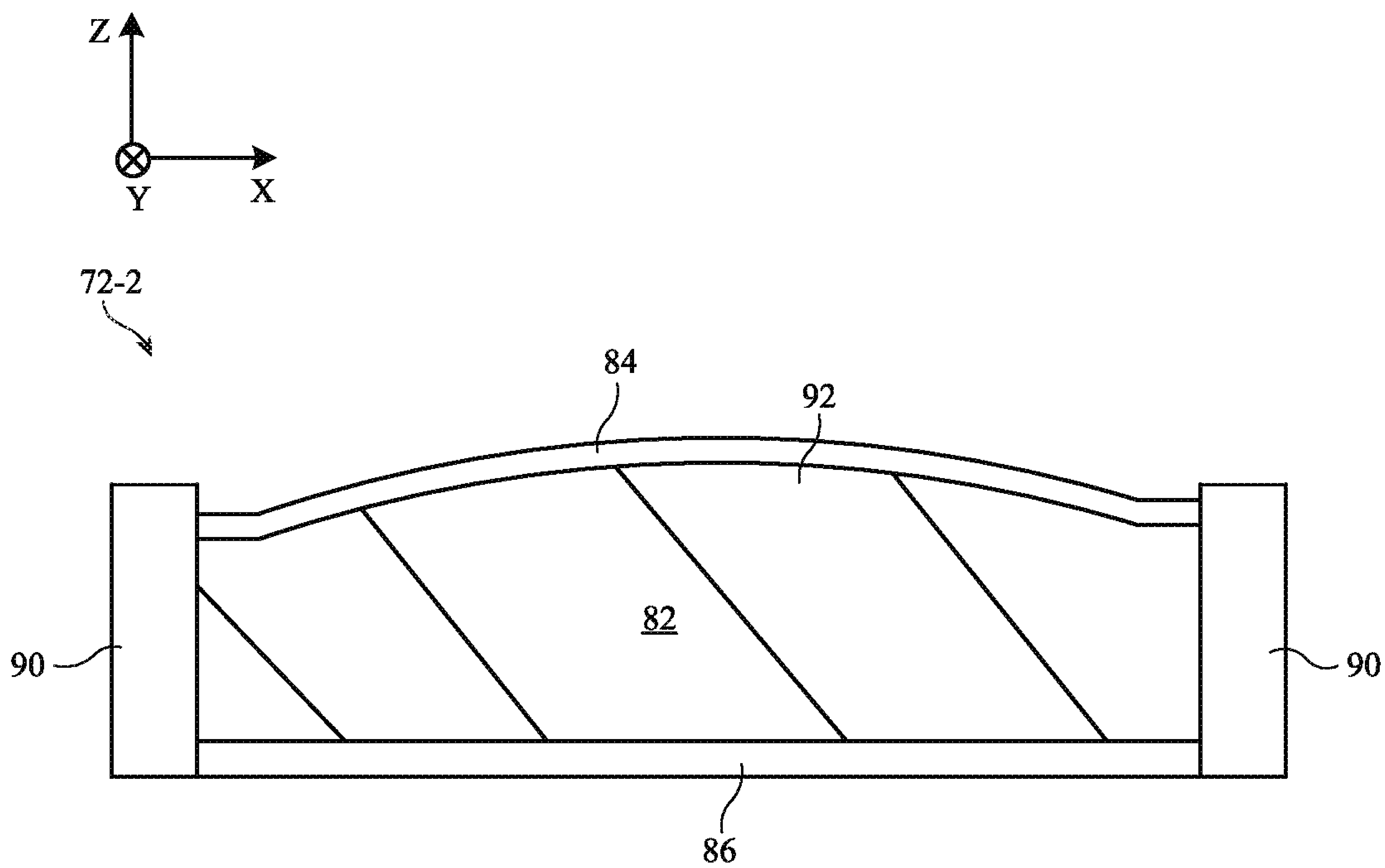


FIG. 4

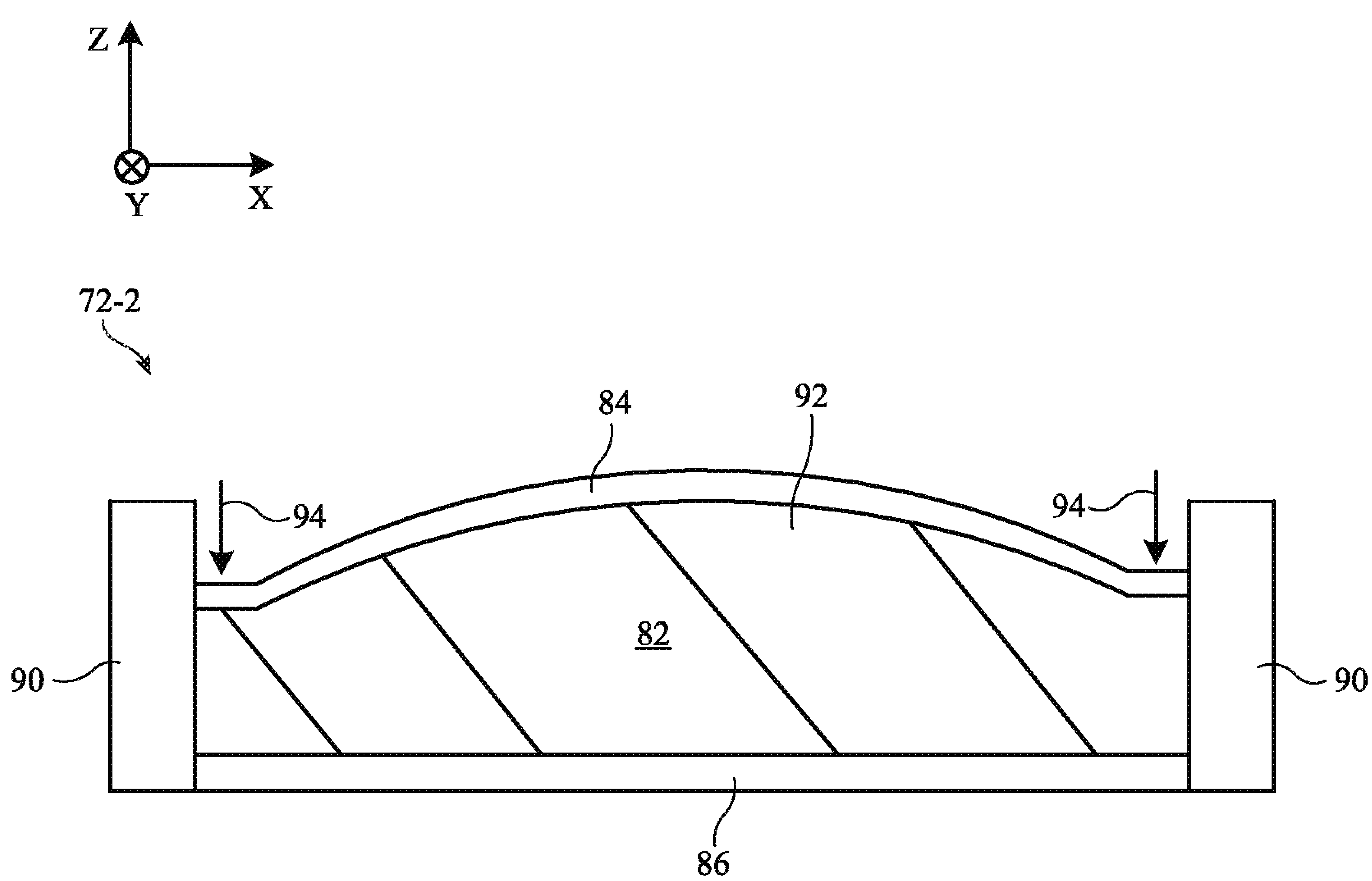


FIG. 5

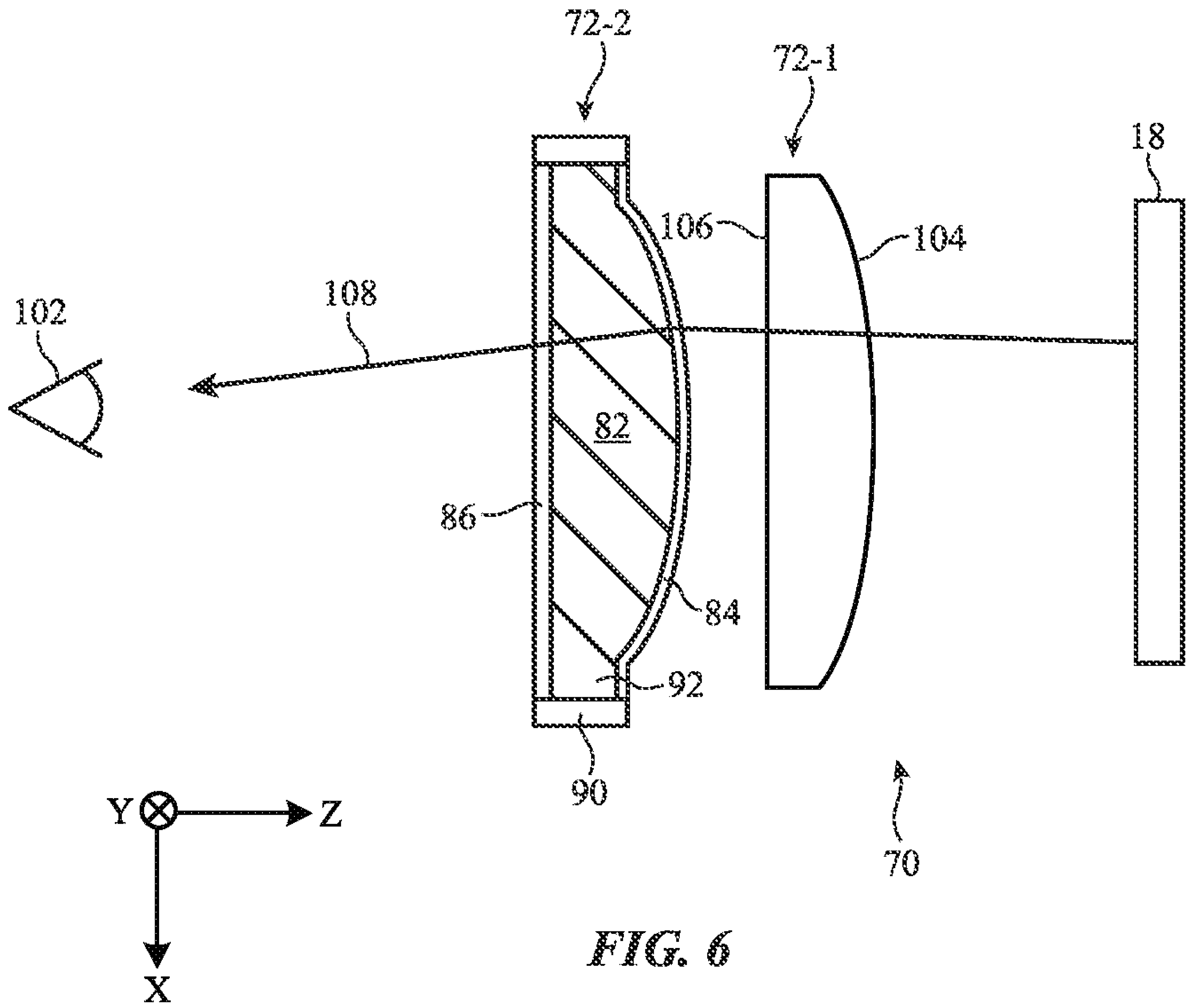
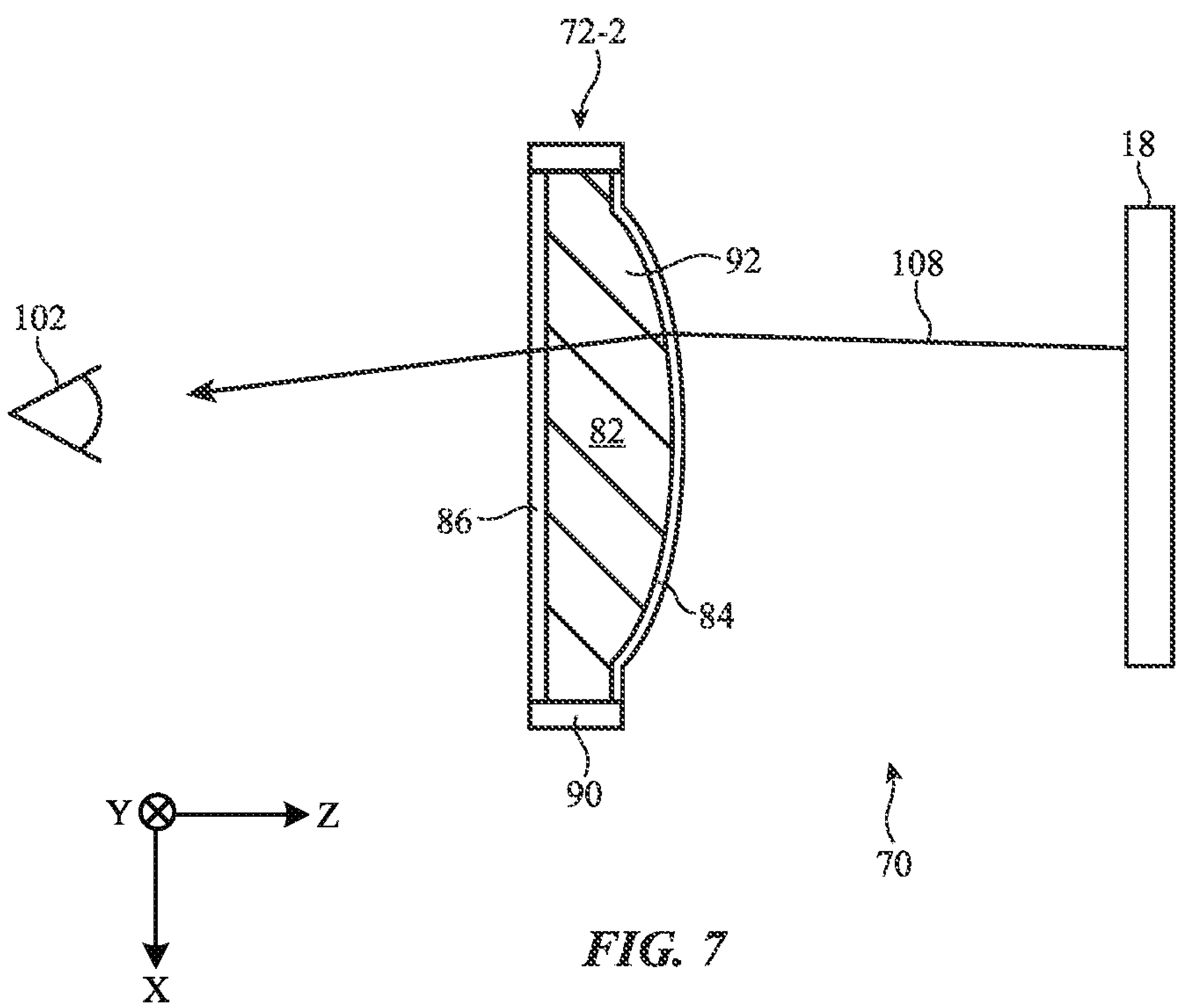

72-2
72-1
18
106
104
108
102
82
86
84
92
90
70
Y
Z
X

FIG. 6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102
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84
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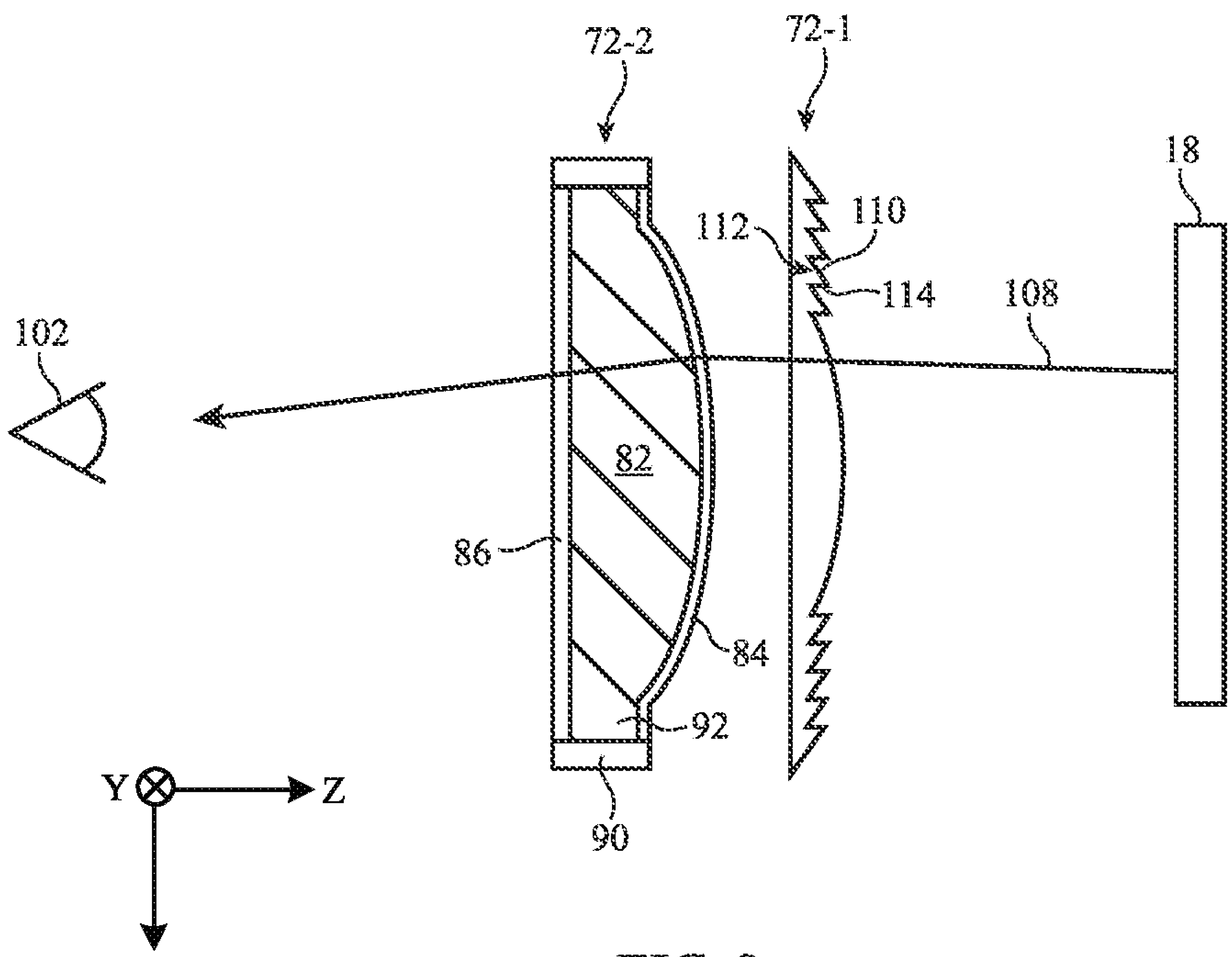
70
Y
Z
X

FIG. 7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114
108
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82
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84
92
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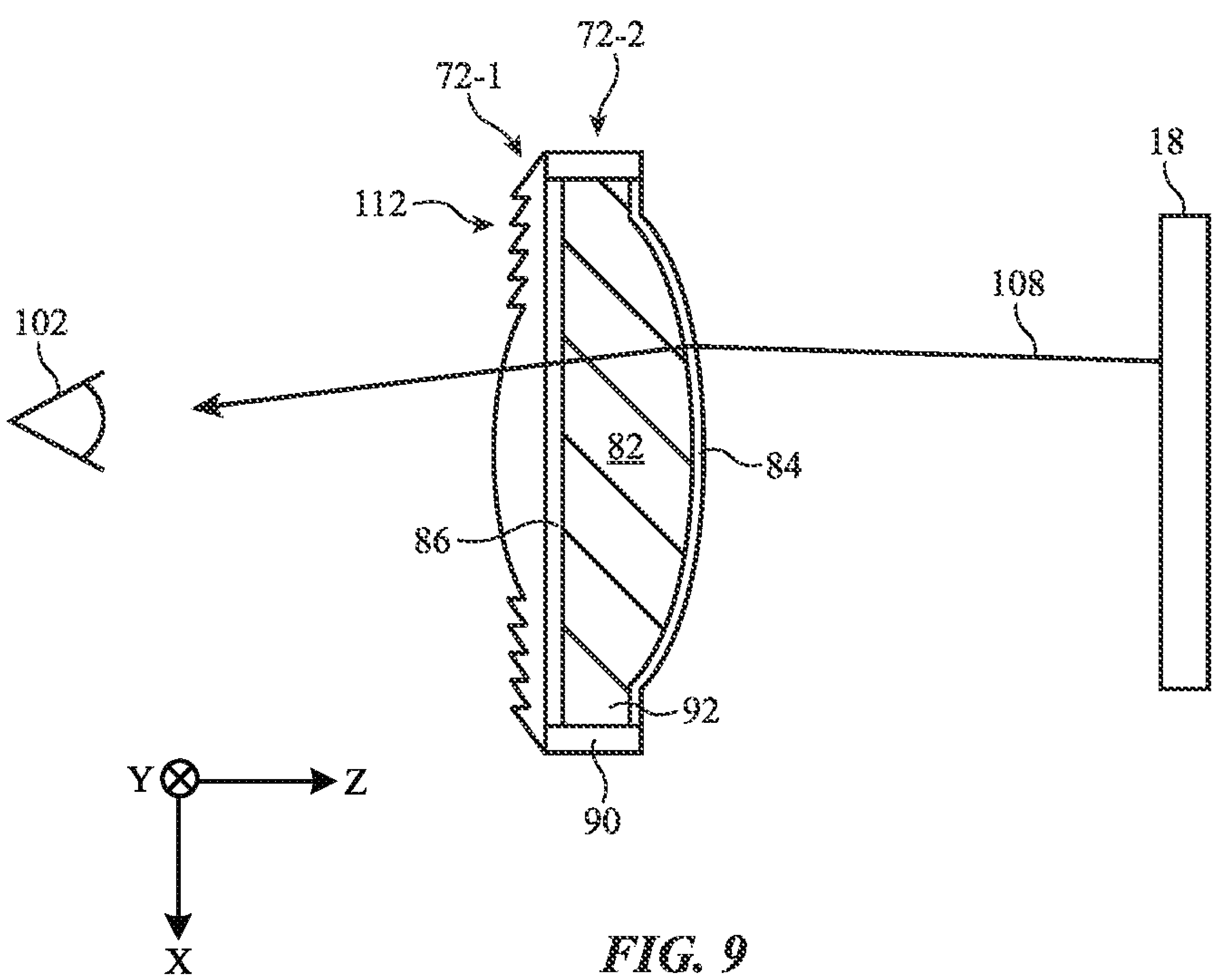
Y
Z
X

FIG. 8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108
102
82
84
86
92
90
Y
Z
X

FIG. 9

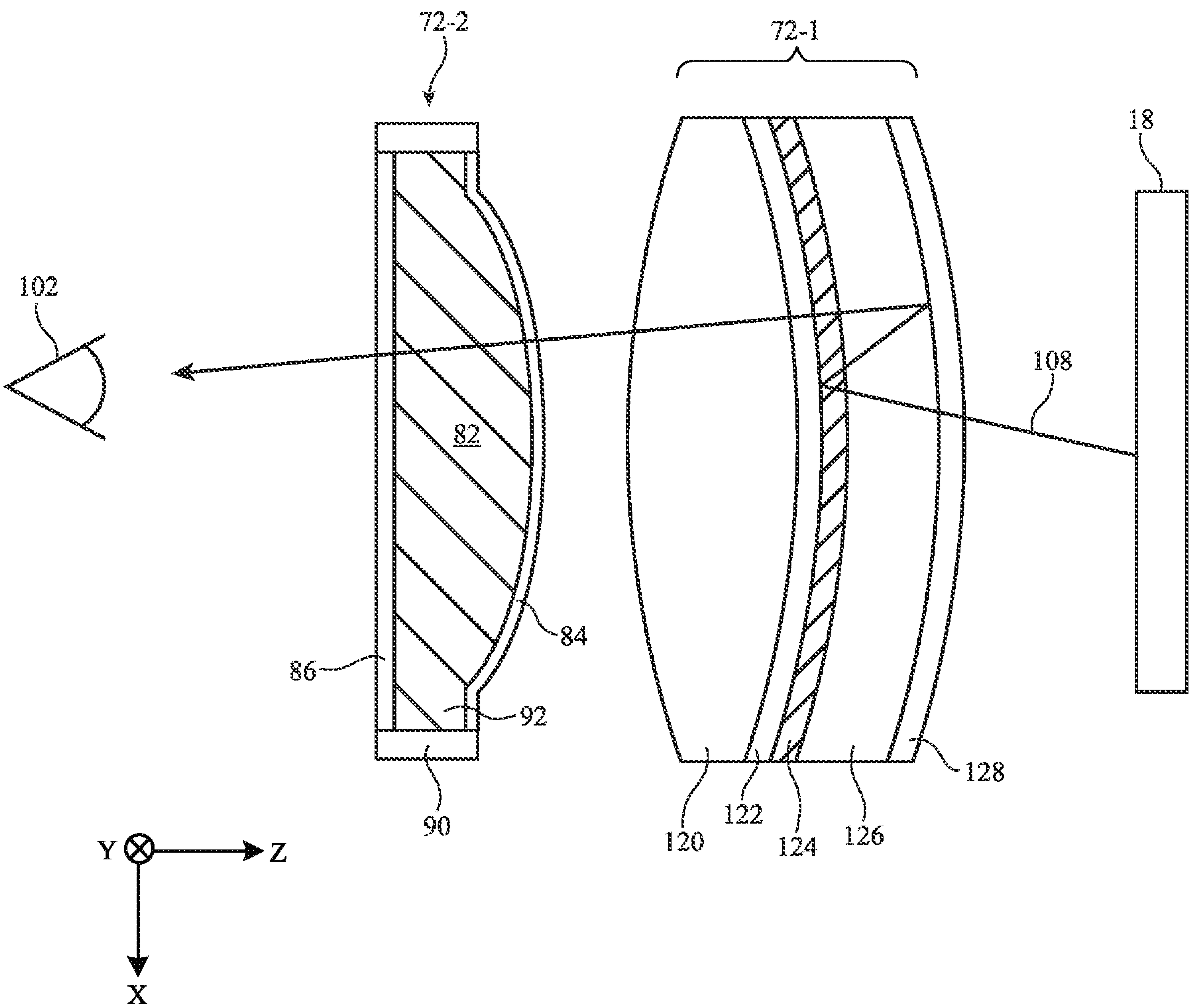


FIG. 10

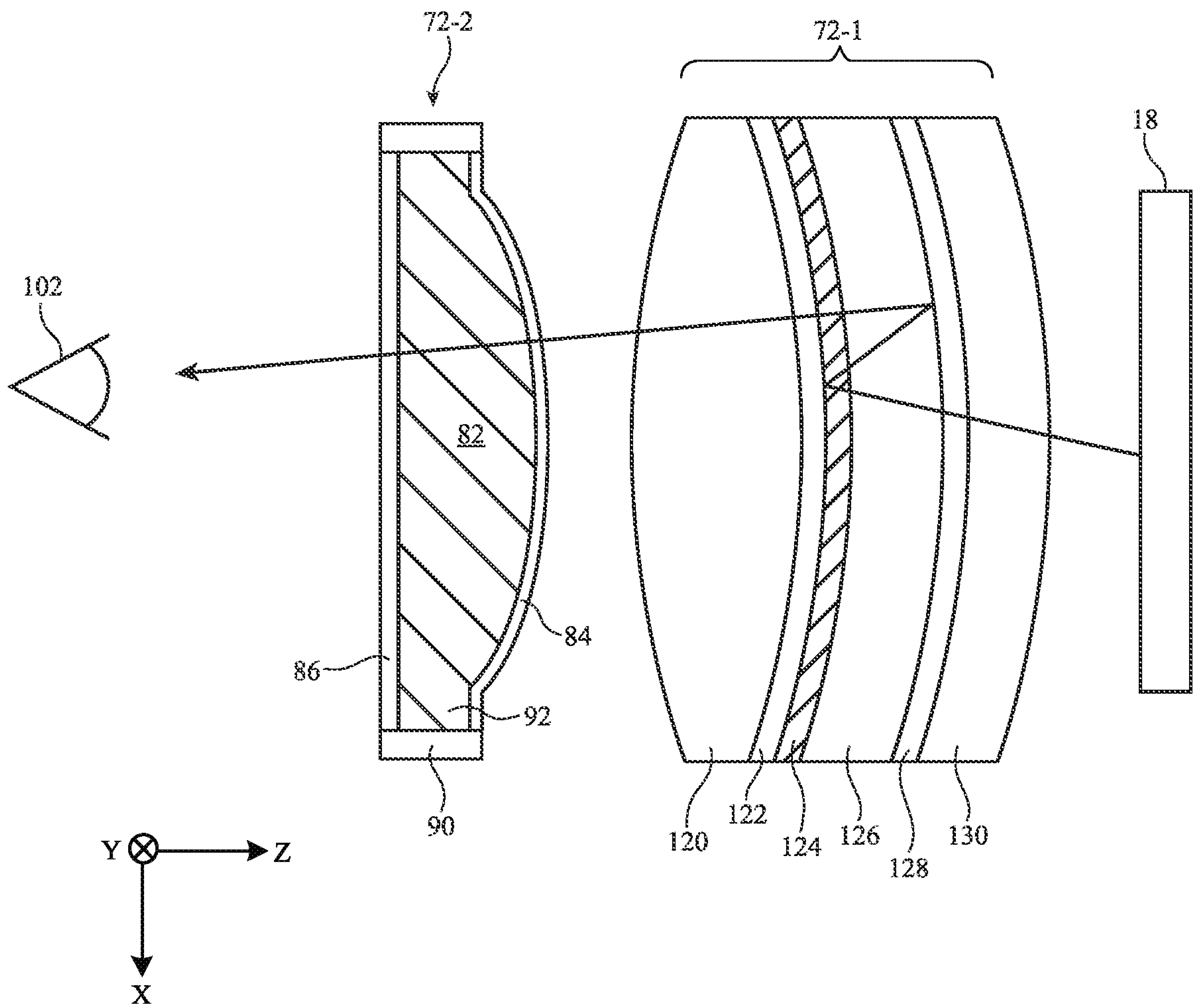


FIG. 11

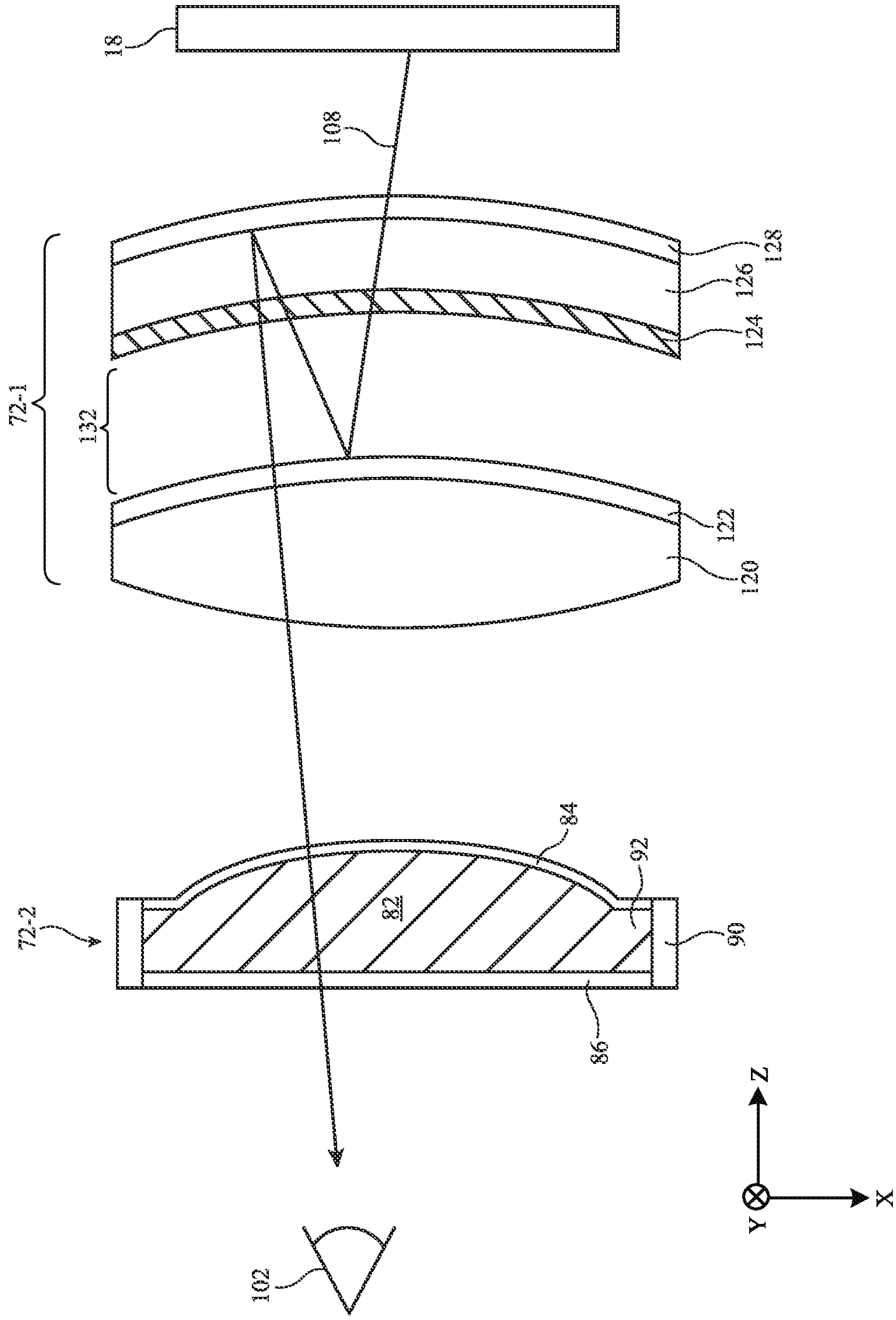


FIG. 12

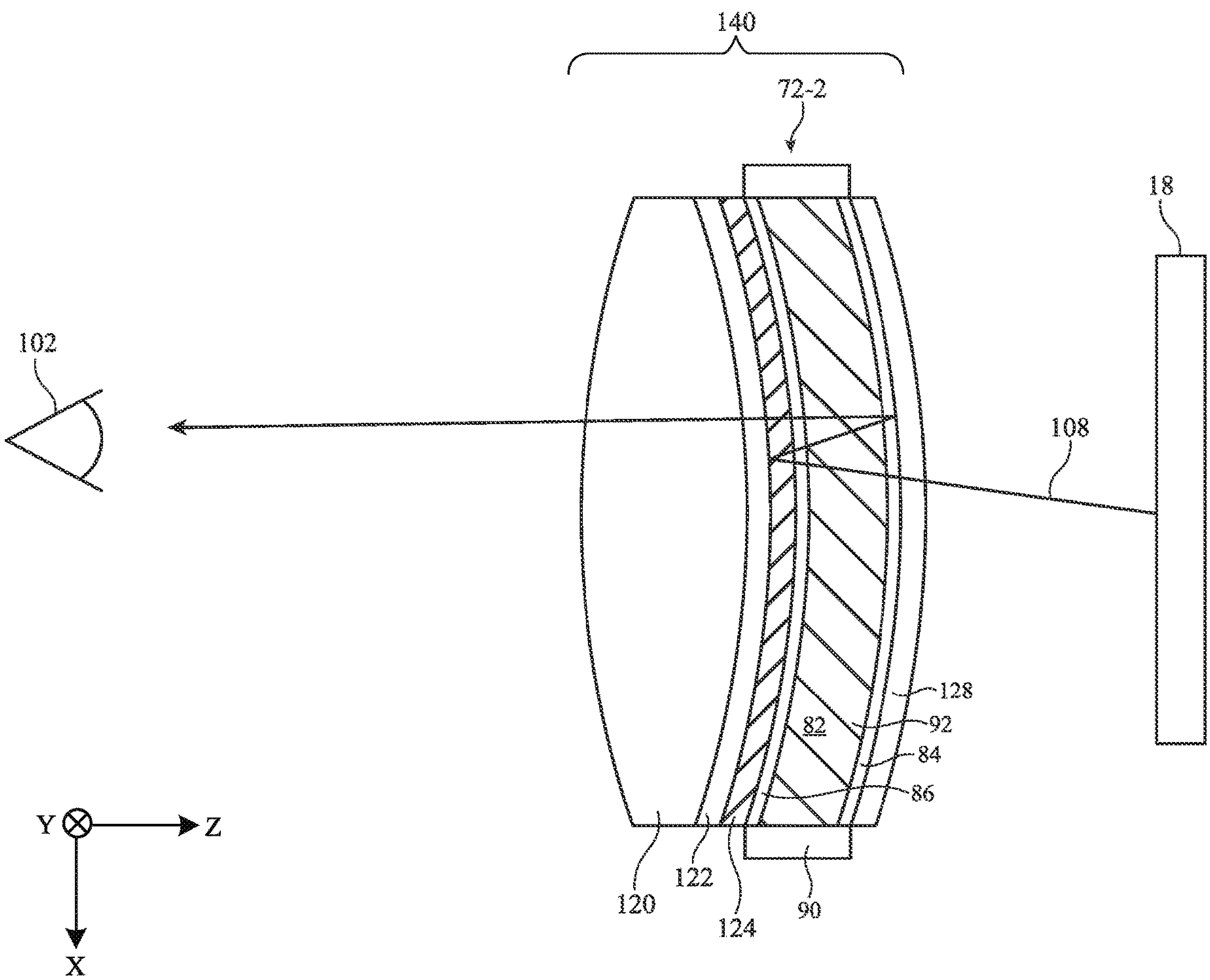


FIG. 13

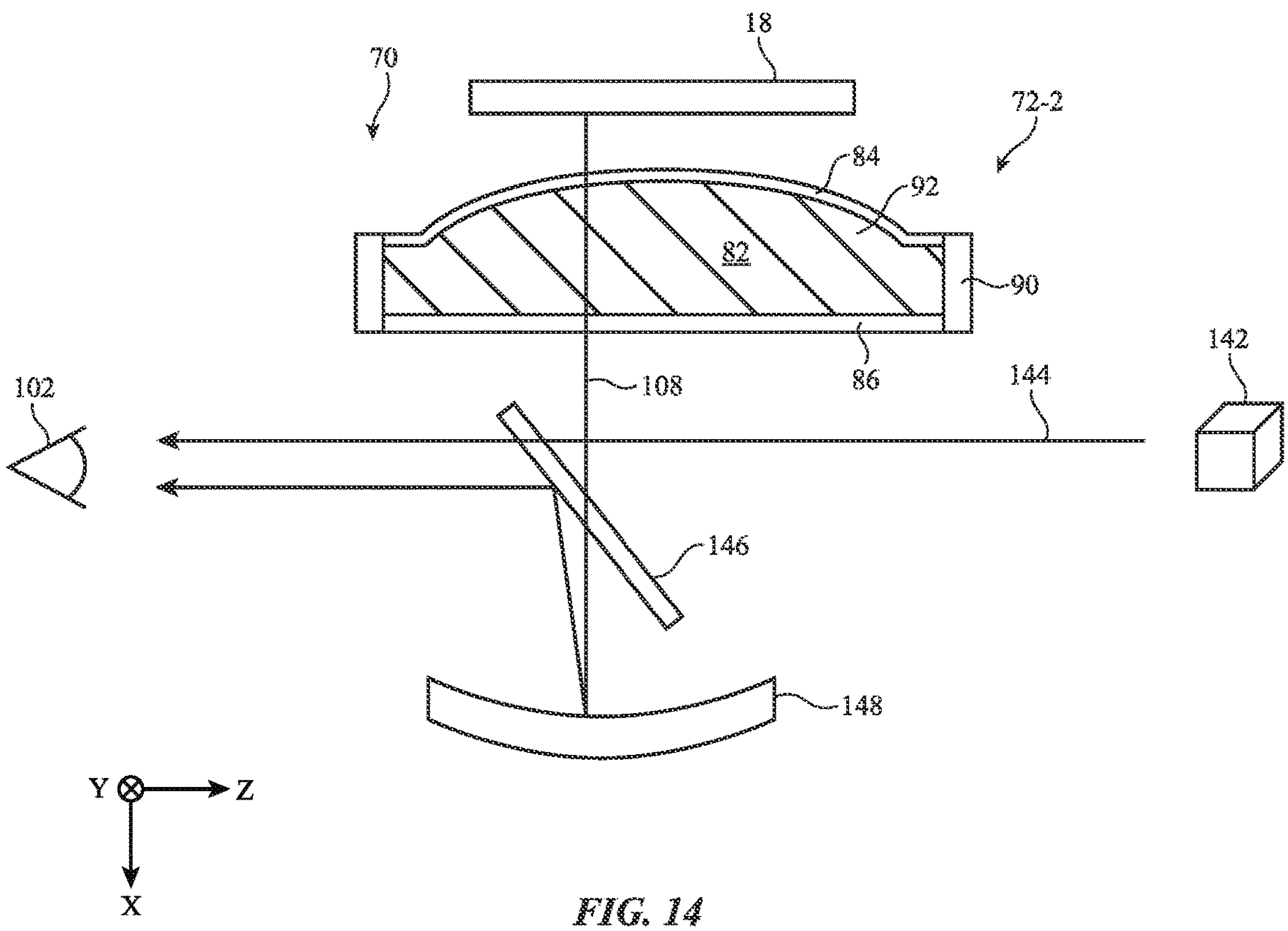


FIG. 14

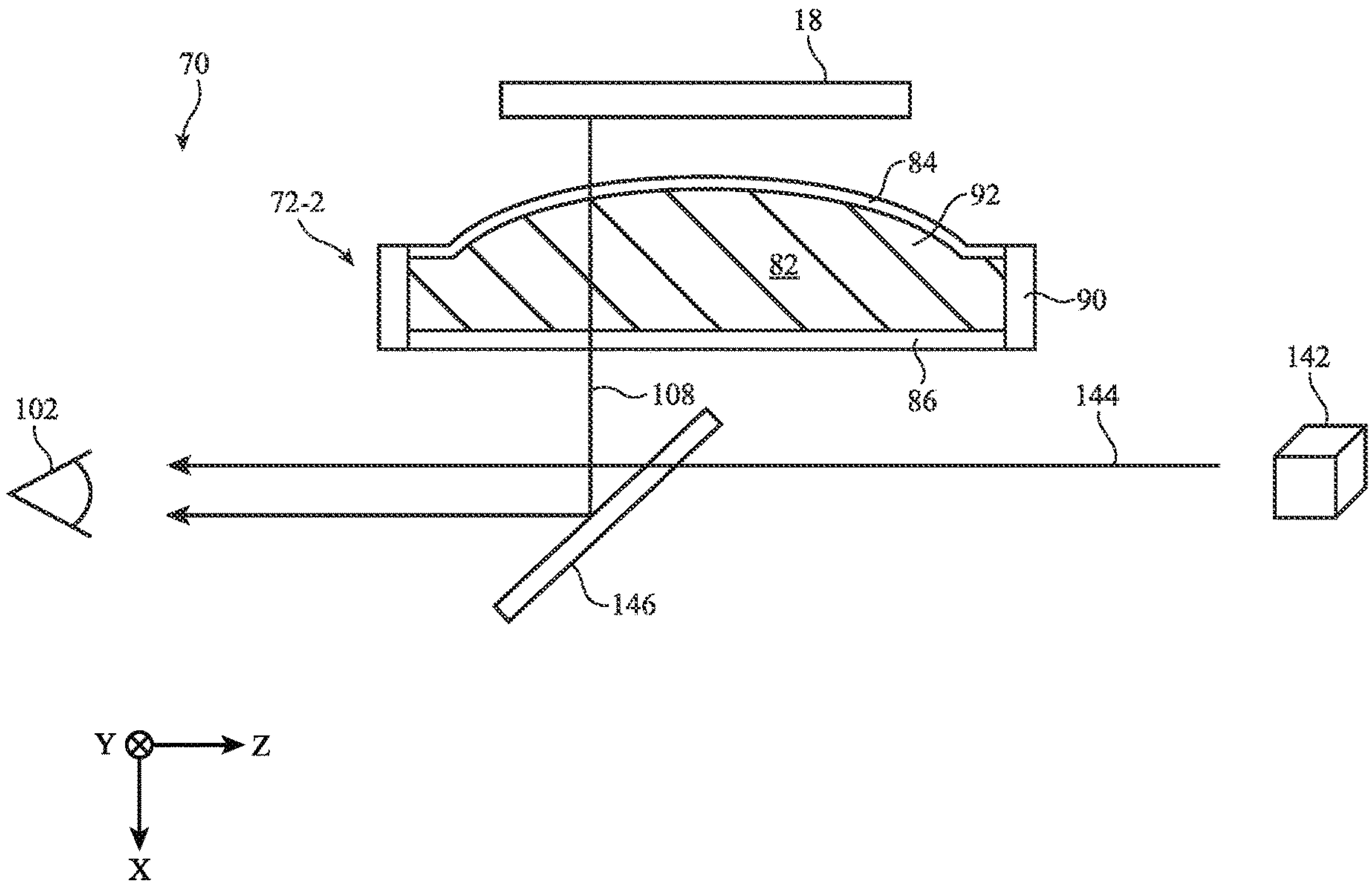


FIG. 15

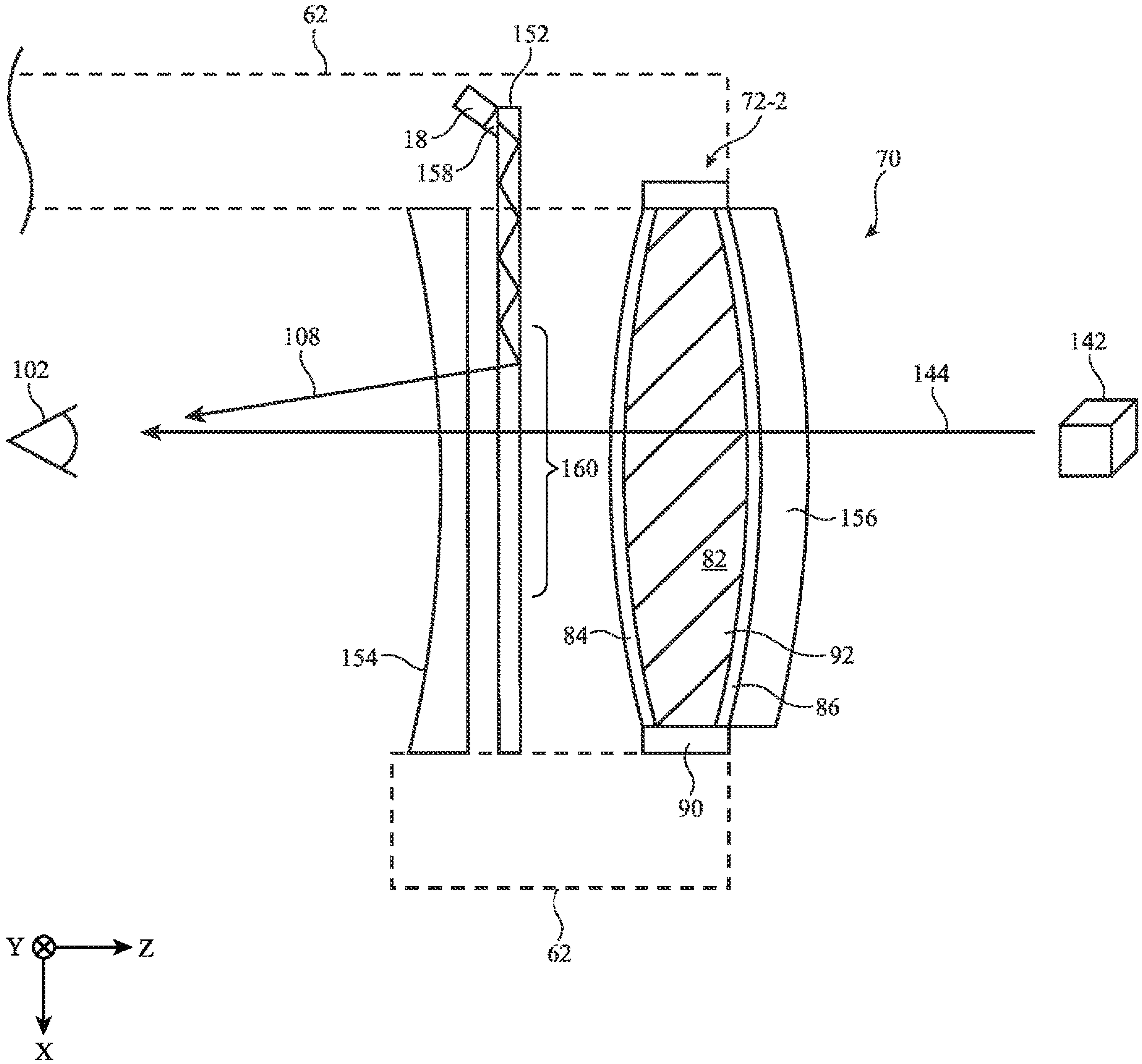

62
152
72-2
70
18
158
108
142
102
144
160
156
82
84
92
154
86
90
62
Y
Z
X

FIG. 16

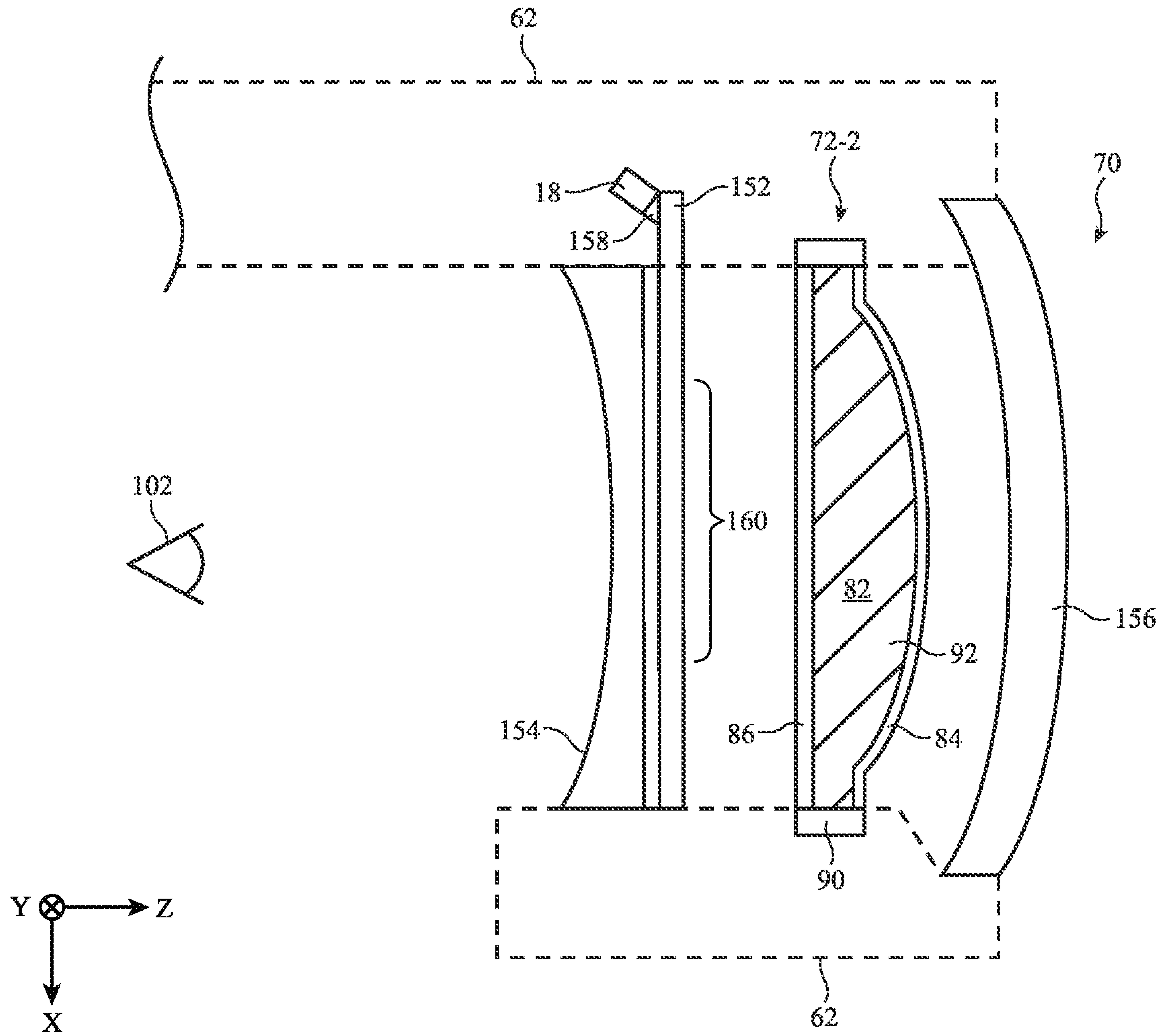
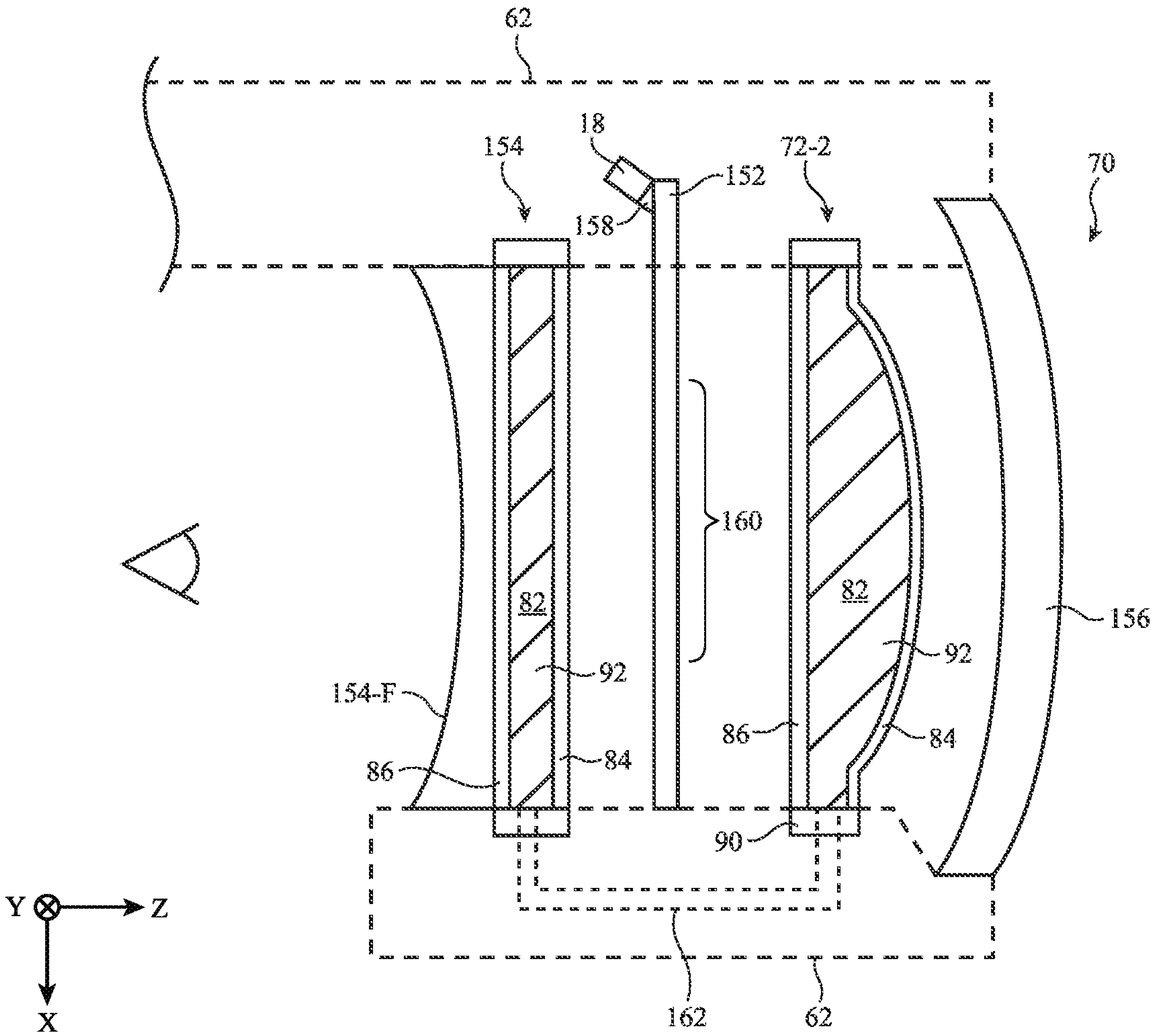


FIG. 17


62
18
154
152
72-2
70
158
160
82
82
92
92
154-F
86
84
86
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90
156
Y
Z
X
162
62

FIG. 18

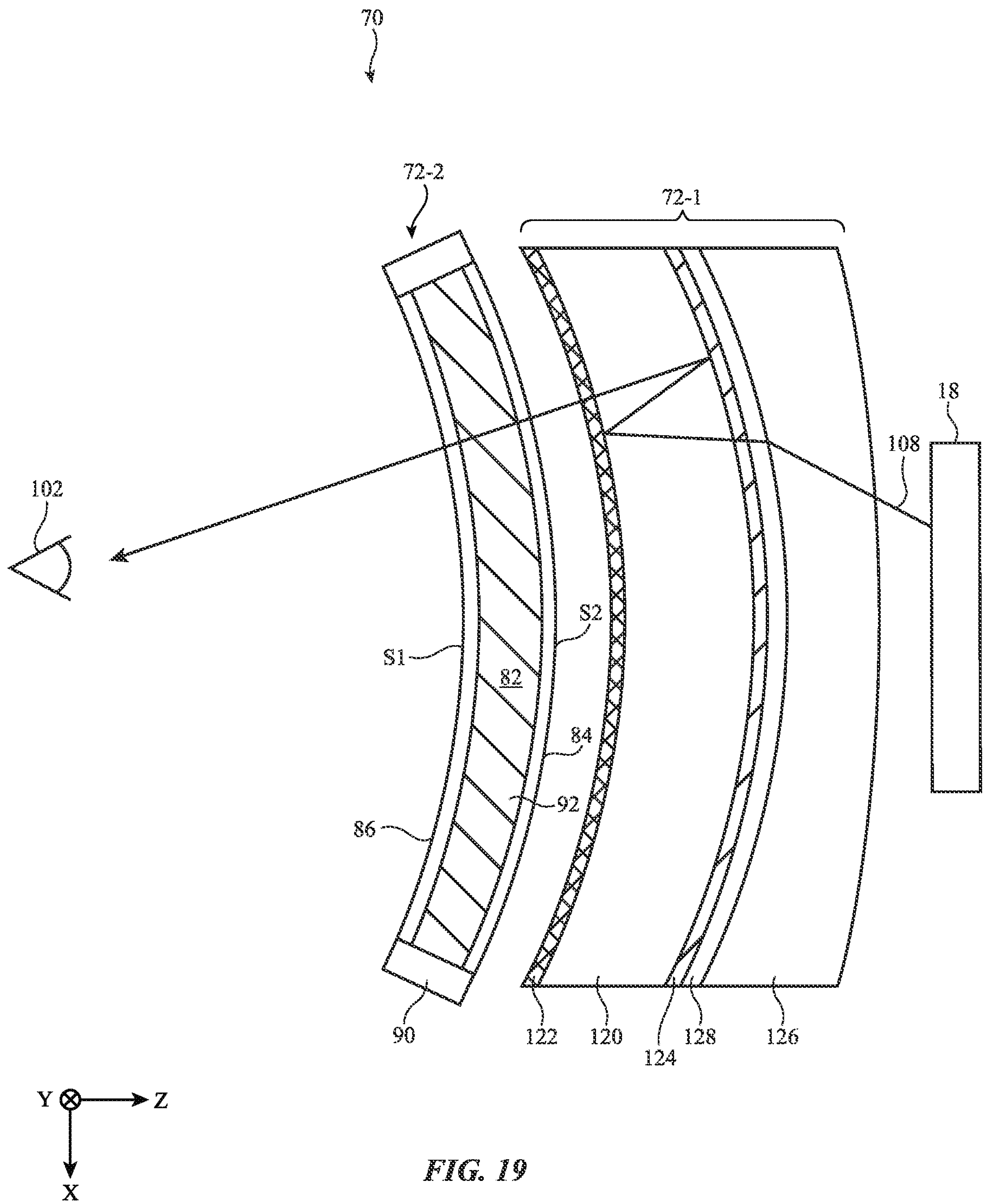

FIG. 19

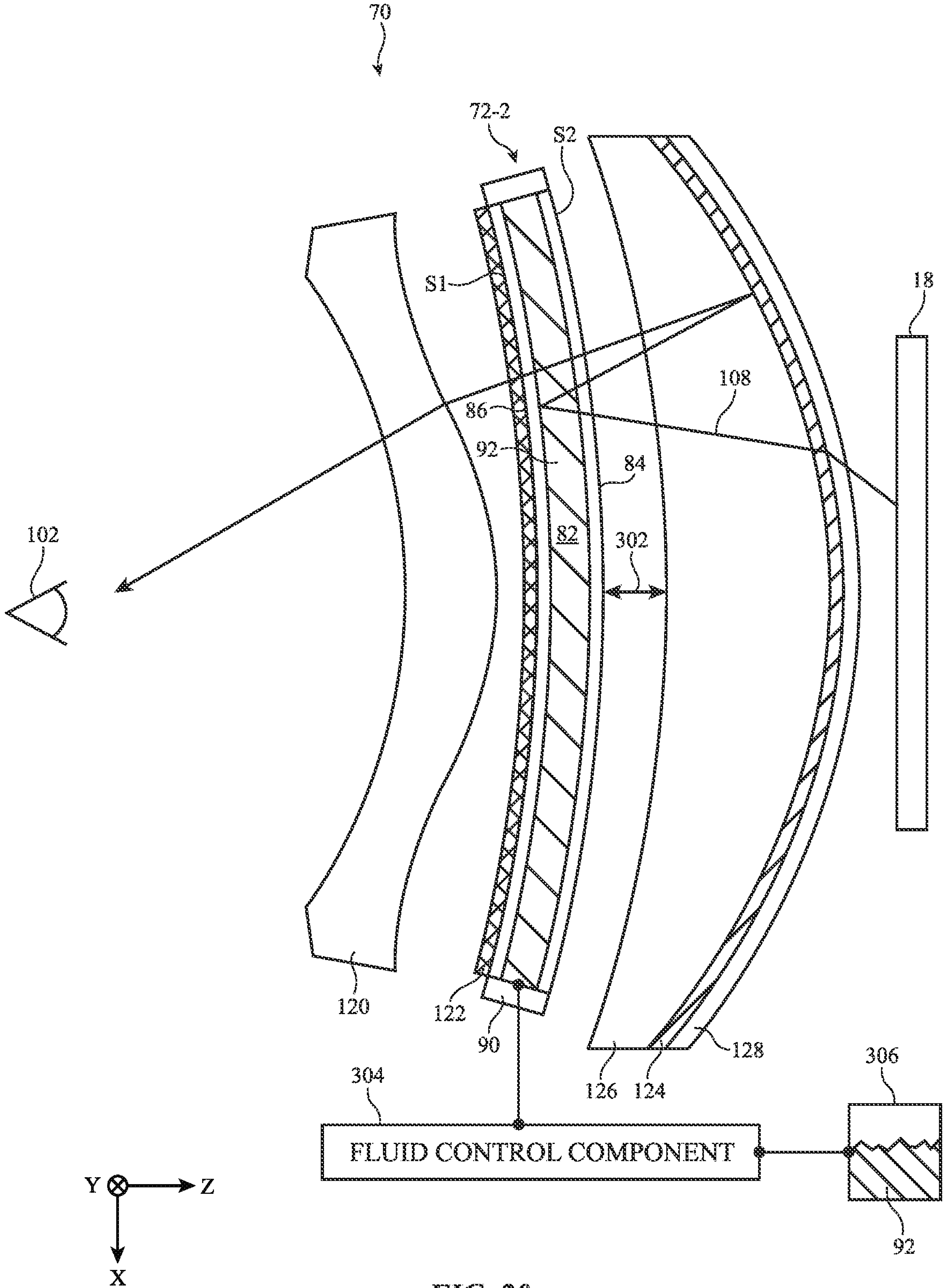
70
72-2
S2
S1
18
108
86
92
84
82
102
302
120
122
90
126
124
128
304
FLUID CONTROL COMPONENT
306
92
Y
Z
X

FIG. 20

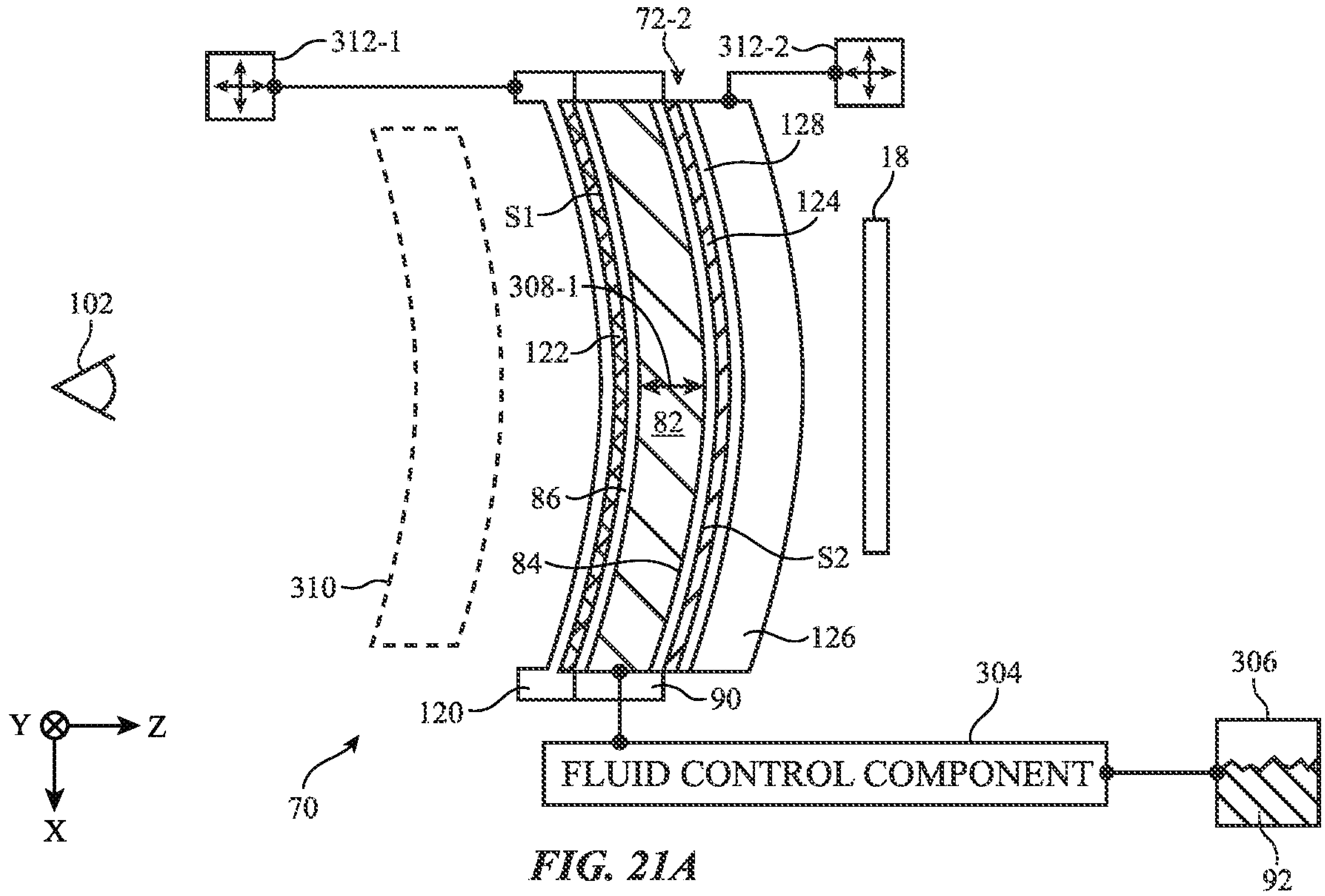

FIG. 21A

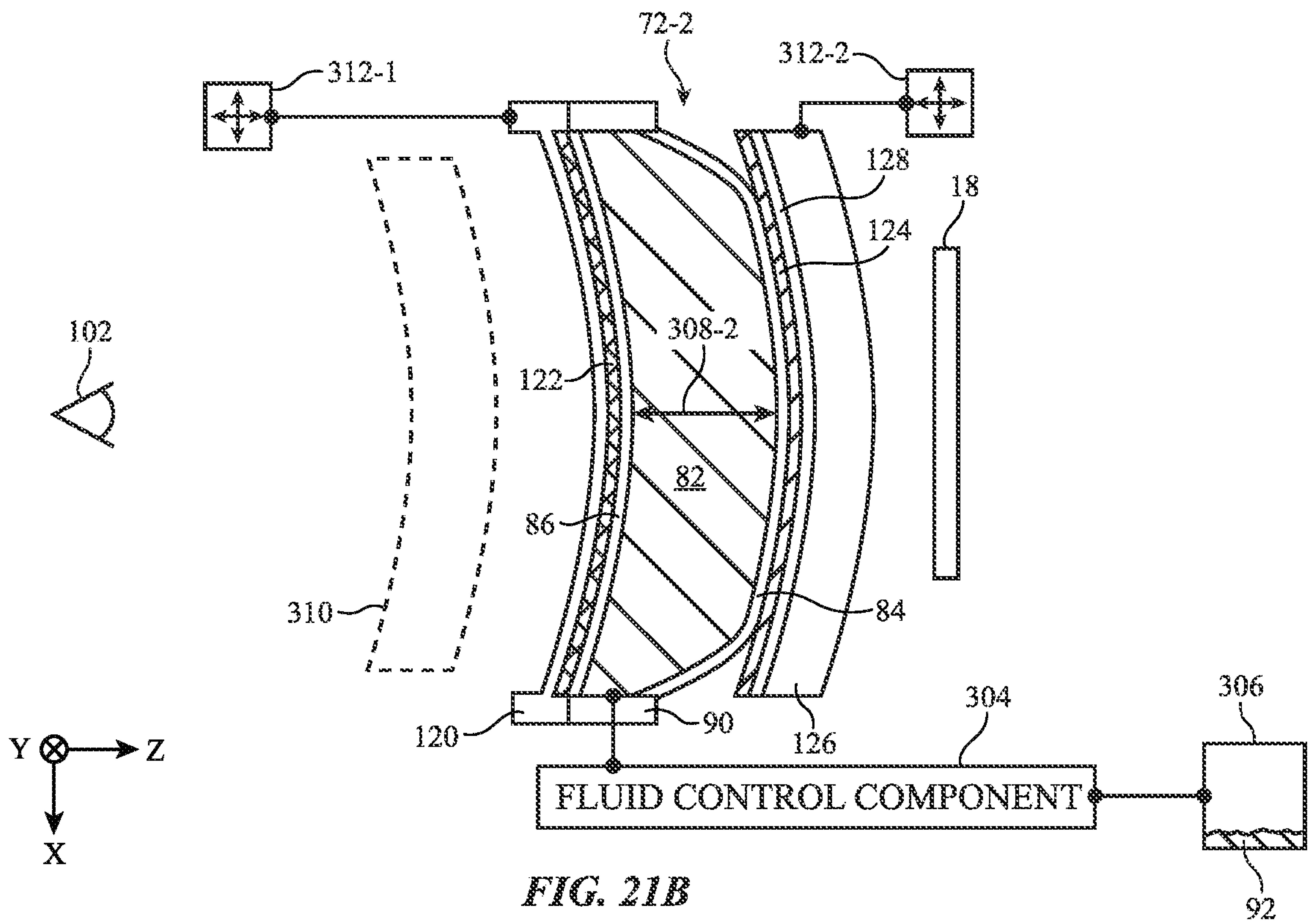

FIG. 21B

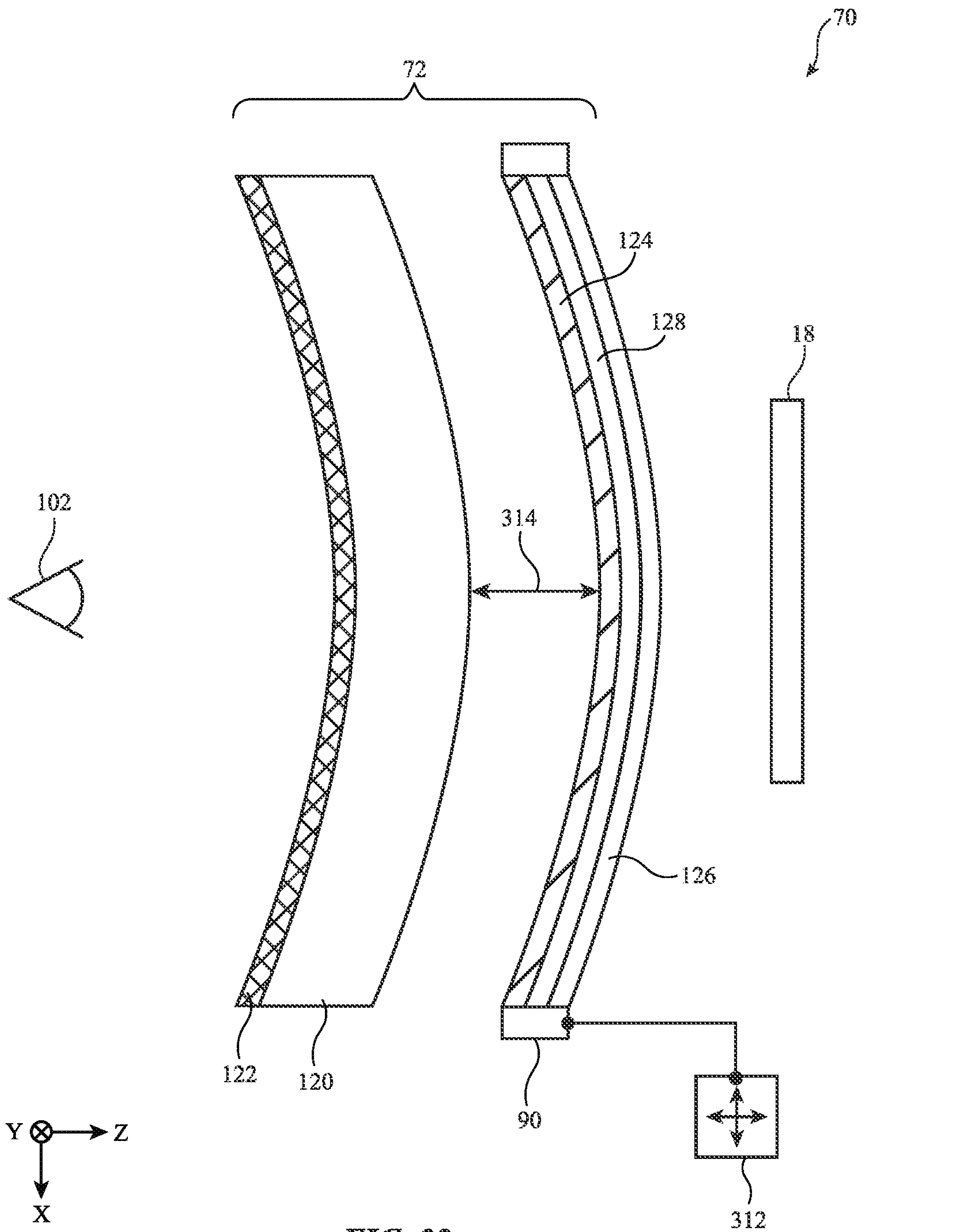

FIG. 22

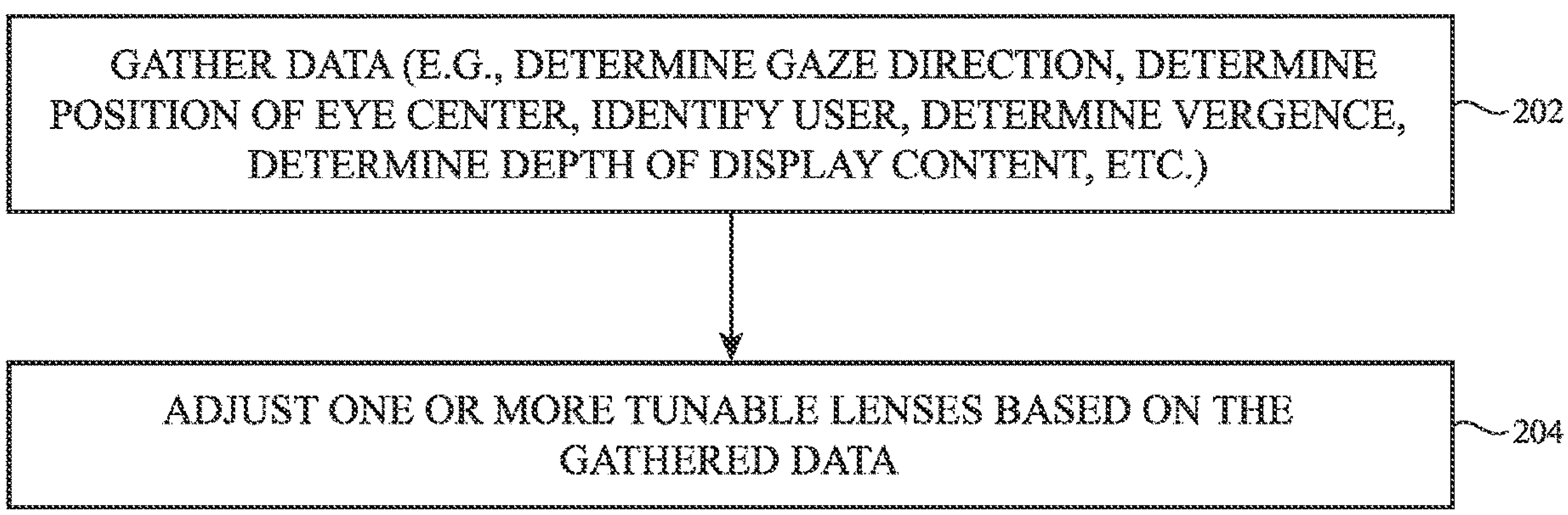
GATHER DATA (E.G., DETERMINE GAZE DIRECTION, DETERMINE POSITION OF EYE CENTER, IDENTIFY USER, DETERMINE VERGENCE, DETERMINE DEPTH OF DISPLAY CONTENT, ETC.)
202
ADJUST ONE OR MORE TUNABLE LENSES BASED ON THE GATHERED DATA
204

FIG. 23

ELECTRONIC DEVICES WITH TUNABLE LENSES

[0001] This application claims the benefit of U.S. provisional patent application No. 63/512,875filed Jul. 10, 2023, and U.S. provisional patent application No. 63/512,870, filed Jul. 10, 2023, which are hereby incorporated by reference herein in their entireties.

BACKGROUND

[0002] This relates generally to electronic devices and, more particularly, to wearable electronic device systems.

[0003] Electronic devices are sometimes configured to be worn by users. For example, head-mounted devices are provided with head-mounted structures that allow the devices to be worn on users' heads. The head-mounted devices may include optical systems with lenses.

[0004] Head-mounted devices typically include lenses with fixed shapes and properties. If care is not taken, it may be difficult to adjust these types of lenses to optimally present content to each user of the head-mounted device.

SUMMARY

[0005] An electronic device may include a head-mounted support structure, a lens module coupled to the head-mounted support structure and comprising a catadioptric lens and a tunable lens, and a display that is viewable through the lens module.

[0006] An electronic device may include a head-mounted support structure, a lens module coupled to the head-mounted support structure and comprising a tunable lens and a Fresnel lens element, and a display that is viewable through the lens module.

[0007] An electronic device may include a head-mounted support structure, a catadioptric lens module coupled to the head-mounted support structure and comprising a tunable lens element, a partially reflective layer, a quarter wave plate, and a reflective polarizer, and a display that is viewable through the catadioptric lens module.

[0008] An electronic device may include a head-mounted support structure and an optical module coupled to the head-mounted support structure. The optical module may include a waveguide having first and second opposing sides, a display that is configured to emit light into the waveguide, a negative bias lens on the first side of the waveguide, and an adjustable positive bias lens on the second side of the waveguide.

[0009] An electronic device may include a head-mounted support structure and an optical module coupled to the head-mounted support structure. The optical module may include a display, a partially reflective layer, a tunable lens element, and a reflective layer with a surface having concave curvature.

[0010] An electronic device may include a head-mounted support structure and an optical module coupled to the head-mounted support structure. The optical module may include a display, a partially reflective layer, and a tunable lens element that is interposed between the display and the partially reflective layer.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a schematic diagram of an illustrative electronic device in accordance with some embodiments.

[0012] FIG. **2** is a top view of an illustrative head-mounted device with a lens module in accordance with some embodiments.

[0013] FIG. **3** is a side view of an illustrative lens module in accordance with some embodiments.

[0014] FIGS. **4** and **5** are side views of an illustrative tunable lens in different tuning states in accordance with some embodiments.

[0015] FIG. **6** is a side view of an illustrative optical module with a tunable lens, a non-adjustable lens element having convex curvature, and a display in accordance with some embodiments.

[0016] FIG. **7** is a side view of an illustrative optical module with a tunable lens and a display in accordance with some embodiments.

[0017] FIG. **8** is a side view of an illustrative optical module with a tunable lens, a Fresnel lens element, and a display in accordance with some embodiments.

[0018] FIG. **9** is a side view of an illustrative optical module with a tunable lens that has an integrated Fresnel lens element in accordance with some embodiments.

[0019] FIG. **10** is a side view of an illustrative optical module with a tunable lens, a catadioptric lens that includes two lens elements, and a display in accordance with some embodiments.

[0020] FIG. **11** is a side view of an illustrative optical module with a tunable lens, a catadioptric lens that includes three lens elements, and a display in accordance with some embodiments.

[0021] FIG. **12** is a side view of an illustrative optical module with a tunable lens, a catadioptric lens that includes two lens elements separated by an air gap, and a display in accordance with some embodiments.

[0022] FIG. **13** is a side view of an illustrative optical module with a catadioptric lens that includes a tunable lens element in accordance with some embodiments.

[0023] FIG. **14** is a side view of an illustrative optical module with a birdbath architecture that includes a tunable lens in accordance with some embodiments.

[0024] FIG. **15** is a side view of an illustrative optical module with a tunable lens interposed between a display and a partially reflective layer in accordance with some embodiments.

[0025] FIG. **16** is a side view of an illustrative optical module with a waveguide, a non-adjustable negative bias lens, and an adjustable positive bias lens that directly contacts a cover layer in accordance with some embodiments.

[0026] FIG. **17** is a side view of an illustrative optical module with a waveguide, a non-adjustable negative bias lens, and an adjustable positive bias lens that is separated from a cover layer by an air gap in accordance with some embodiments.

[0027] FIG. **18** is a side view of an illustrative optical module with a waveguide, an adjustable negative bias lens, and an adjustable positive bias lens in accordance with some embodiments.

[0028] FIG. **19** is a side view of an illustrative optical module with a tunable lens having an aspheric concave surface and an adjustable convex surface in accordance with some embodiments.

[0029] FIG. **20** is a side view of an illustrative optical module with a tunable lens interposed between first and second additional lens elements and separated from the first and second additional lens elements by air gaps in accordance with some embodiments.

[0030] FIGS. **21**A and **21**B are side views of an illustrative optical module with a fluid control component that adjusts the thickness of a fluid-filled chamber in a tunable lens in accordance with some embodiments.

[0031] FIG. **22** is a side view of an illustrative optical module with an adjustable partially reflective layer in accordance with some embodiments.

[0032] FIG. **23** is a flowchart of an illustrative method for operating an electronic device with a tunable lens in accordance with some embodiments.

DETAILED DESCRIPTION

[0033] A schematic diagram of an illustrative electronic device is shown in FIG. **1**. As shown in FIG. **1**, electronic device **10** (sometimes referred to as head-mounted device **10**, system **10**, head-mounted display **10**, etc.) may have control circuitry **14**. In addition to being a head-mounted device, electronic device **10** may be other types of electronic devices such as a cellular telephone, laptop computer, speaker, computer monitor, electronic watch, tablet computer, etc. Control circuitry **14** may be configured to perform operations in head-mounted device **10** using hardware (e.g., dedicated hardware or circuitry), firmware and/or software. Software code for performing operations in head-mounted device **10** and other data is stored on non-transitory computer readable storage media (e.g., tangible computer readable storage media) in control circuitry **14**. The software code may sometimes be referred to as software, data, program instructions, instructions, or code. The non-transitory computer readable storage media (sometimes referred to generally as memory) may include non-volatile memory such as non-volatile random-access memory (NVRAM), one or more hard drives (e.g., magnetic drives or solid-state drives), one or more removable flash drives or other removable media, or the like. Software stored on the non-transitory computer readable storage media may be executed on the processing circuitry of control circuitry **14**. The processing circuitry may include application-specific integrated circuits with processing circuitry, one or more microprocessors, digital signal processors, graphics processing units, a central processing unit (CPU) or other processing circuitry.

[0034] Head-mounted device **10** may include input-output circuitry **16**. Input-output circuitry **16** may be used to allow a user to provide head-mounted device **10** with user input. Input-output circuitry **16** may also be used to gather information on the environment in which head-mounted device **10** is operating. Output components in circuitry **16** may allow head-mounted device **10** to provide a user with output.

[0035] As shown in FIG. **1**, input-output circuitry **16** may include a display such as display **18**. Display **18** may be used to display images for a user of head-mounted device **10**. Display **18** may be a transparent or translucent display so that a user may observe physical objects through the display while computer-generated content is overlaid on top of the physical objects by presenting computer-generated images on the display. A transparent or translucent display may be formed from a transparent or translucent pixel array (e.g., a transparent organic light-emitting diode display panel) or may be formed by a display device that provides images to a user through a transparent structure such as a beam splitter, holographic coupler, or other optical coupler (e.g., a display device such as a liquid crystal on silicon display). Alternatively, display **18** may be an opaque display that blocks light from physical objects when a user operates head-mounted device **10**. In this type of arrangement, a pass-through camera may be used to display physical objects to the user. The pass-through camera may capture images of the physical environment and the physical environment images may be displayed on the display for viewing by the user. Additional computer-generated content (e.g., text, game-content, other visual content, etc.) may optionally be overlaid over the physical environment images to provide an extended reality environment for the user. When display **18** is opaque, the display may also optionally display entirely computer-generated content (e.g., without displaying images of the physical environment).

[0036] Display **18** may include one or more optical systems (e.g., lenses) (sometimes referred to as optical assemblies) that allow a viewer to view images on display(s) **18**. A single display **18** may produce images for both eyes or a pair of displays **18** may be used to display images. In configurations with multiple displays (e.g., left and right eye displays), the focal length and positions of the lenses may be selected so that any gap present between the displays will not be visible to a user (e.g., so that the images of the left and right displays overlap or merge seamlessly). Display modules (sometimes referred to as display assemblies) that generate different images for the left and right eyes of the user may be referred to as stereoscopic displays. The stereoscopic displays may be capable of presenting two-dimensional content (e.g., a user notification with text) and three-dimensional content (e.g., a simulation of a physical object such as a cube).

[0037] The example of device **10** including a display is merely illustrative and display(s) **18** may be omitted from device **10** if desired. Device **10** may include an optical pass-through area where real-world content is viewable to the user either directly or through a tunable lens.

[0038] Input-output circuitry **16** may include various other input-output devices. For example, input-output circuitry **16** may include one or more speakers **20** that are configured to play audio and one or more microphones **26** that are configured to capture audio data from the user and/or from the physical environment around the user.

[0039] Input-output circuitry **16** may also include one or more cameras such as an inward-facing camera **22** (e.g., that face the user's face when the head-mounted device is mounted on the user's head) and an outward-facing camera **24** (that face the physical environment around the user when the head-mounted device is mounted on the user's head). Cameras **22** and **24** may capture visible light images, infrared images, or images of any other desired type. The cameras may be stereo cameras if desired. Inward-facing camera **22** may capture images that are used for gaze-detection operations, in one possible arrangement. Outward-facing camera **24** may capture pass-through video for head-mounted device **10**.

[0040] As shown in FIG. **1**, input-output circuitry **16** may include position and motion sensors **28** (e.g., compasses, gyroscopes, accelerometers, and/or other devices for monitoring the location, orientation, and movement of head-mounted device **10**, satellite navigation system circuitry such as Global Positioning System circuitry for monitoring user location, etc.). Using sensors **28**, for example, control circuitry **14** can monitor the current direction in which a user's head is oriented relative to the surrounding environment (e.g., a user's head pose). One or more of cameras **22** and **24** may also be considered part of position and motion sensors **28**. The cameras may be used for face tracking (e.g., by capturing images of the user's jaw, mouth, etc. while the device is worn on the head of the user), body tracking (e.g., by capturing images of the user's torso, arms, hands, legs, etc. while the device is worn on the head of user), and/or for localization (e.g., using visual odometry, visual inertial odometry, or other simultaneous localization and mapping (SLAM) technique).

[0041] Input-output circuitry **16** may also include other sensors and input-output components if desired. As shown in FIG. **1**, input-output circuitry **16** may include an ambient light sensor **30**. The ambient light sensor may be used to measure ambient light levels around head-mounted device **10**. The ambient light sensor may measure light at one or more wavelengths (e.g., different colors of visible light and/or infrared light).

[0042] Input-output circuitry **16** may include a magnetometer **32**. The magnetometer may be used to measure the strength and/or direction of magnetic fields around head-mounted device **10**.

[0043] Input-output circuitry **16** may include a heart rate monitor **34**. The heart rate monitor may be used to measure the heart rate of a user wearing head-mounted device **10** using any desired techniques.

[0044] Input-output circuitry **16** may include a depth sensor **36**. The depth sensor may be a pixelated depth sensor (e.g., that is configured to measure multiple depths across the physical environment) or a point sensor (that is configured to measure a single depth in the physical environment). The depth sensor (whether a pixelated depth sensor or a point sensor) may use phase detection (e.g., phase detection autofocus pixel(s)) or light detection and ranging (LIDAR) to measure depth. Any combination of depth sensors may be used to determine the depth of physical objects in the physical environment.

[0045] Input-output circuitry **16** may include a temperature sensor **38**. The temperature sensor may be used to measure the temperature of a user of head-mounted device **10**, the temperature of head-mounted device **10** itself, or an ambient temperature of the physical environment around head-mounted device **10**.

[0046] Input-output circuitry **16** may include a touch sensor **40**. The touch sensor may be, for example, a capacitive touch sensor that is configured to detect touch from a user of the head-mounted device.

[0047] Input-output circuitry **16** may include a moisture sensor **42**. The moisture sensor may be used to detect the presence of moisture (e.g., water) on, in, or around the head-mounted device.

[0048] Input-output circuitry **16** may include a gas sensor **44**. The gas sensor may be used to detect the presence of one or more gases (e.g., smoke, carbon monoxide, etc.) in or around the head-mounted device.

[0049] Input-output circuitry **16** may include a barometer **46**. The barometer may be used to measure atmospheric pressure, which may be used to determine the elevation above sea level of the head-mounted device.

[0050] Input-output circuitry **16** may include a gaze-tracking sensor **48** (sometimes referred to as gaze-tracker **48** and gaze-tracking system **48**). The gaze-tracking sensor **48** may include a camera and/or other gaze-tracking sensor components (e.g., light sources that emit beams of light so that reflections of the beams from a user's eyes may be detected) to monitor the user's eyes. Gaze-tracker **48** may face a user's eyes and may track a user's gaze. A camera in the gaze-tracking system may determine the location of a user's eyes (e.g., the centers of the user's pupils), may determine the direction in which the user's eyes are oriented (the direction of the user's gaze), may determine the user's pupil size (e.g., so that light modulation and/or other optical parameters and/or the amount of gradualness with which one or more of these parameters is spatially adjusted and/or the area in which one or more of these optical parameters is adjusted is adjusted based on the pupil size), may be used in monitoring the current focus of the lenses in the user's eyes (e.g., whether the user is focusing in the near field or far field, which may be used to assess whether a user is day dreaming or is thinking strategically or tactically), and/or other gaze information. Cameras in the gaze-tracking system may sometimes be referred to as inward-facing cameras, gaze-detection cameras, eye-tracking cameras, gaze-tracking cameras, or eye-monitoring cameras. If desired, other types of image sensors (e.g., infrared and/or visible light-emitting diodes and light detectors, etc.) may also be used in monitoring a user's gaze. The use of a gaze-detection camera in gaze-tracker **48** is merely illustrative.

[0051] Input-output circuitry **16** may include a button **50**. The button may include a mechanical switch that detects a user press during operation of the head-mounted device.

[0052] Input-output circuitry **16** may include a light-based proximity sensor **52**. The light-based proximity sensor may include a light source (e.g., an infrared light source) and an image sensor (e.g., an infrared image sensor) configured to detect reflections of the emitted light to determine proximity to nearby objects.

[0053] Input-output circuitry **16** may include a global positioning system (GPS) sensor **54**. The GPS sensor may determine location information for the head-mounted device. The GPS sensor may include one or more antennas used to receive GPS signals. The GPS sensor may be considered a part of position and motion sensors **28**.

[0054] Input-output circuitry **16** may include any other desired components (e.g., capacitive proximity sensors, other proximity sensors, strain gauges, pressure sensors, audio components, haptic output devices such as vibration motors, light-emitting diodes, other light sources, etc.).

[0055] Head-mounted device **10** may also include communication circuitry **56** to allow the head-mounted device to communicate with external equipment (e.g., a tethered computer, a portable device such as a handheld device or laptop computer, one or more external servers, or other electrical equipment). Communication circuitry **56** may be used for both wired and wireless communication with external equipment.

[0056] Communication circuitry **56** may include radio-frequency (RF) transceiver circuitry formed from one or more integrated circuits, power amplifier circuitry, low-noise input amplifiers, passive RF components, one or more antennas, transmission lines, and other circuitry for handling RF wireless signals. Wireless signals can also be sent using light (e.g., using infrared communications).

[0057] The radio-frequency transceiver circuitry in wireless communications circuitry **56** may handle wireless local area network (WLAN) communications bands such as the 2.4 GHZ and 5 GHz Wi-Fi® (IEEE 802.11) bands, wireless personal area network (WPAN) communications bands such as the 2.4 GHz Bluetooth® communications band, cellular telephone communications bands such as a cellular low band (LB) (e.g., 600 to 960 MHZ), a cellular low-midband (LMB) (e.g., 1400 to 1550 MHZ), a cellular midband (MB) (e.g., from 1700 to 2200 MHz), a cellular high band (HB) (e.g., from 2300 to 2700 MHZ), a cellular ultra-high band (UHB) (e.g., from 3300 to 5000 MHz, or other cellular communications bands between about 600 MHz and about 5000 MHz (e.g., 3G bands, 4G LTE bands, 5G New Radio Frequency Range 1 (FR1) bands below 10 GHz, etc.), a near-field communications (NFC) band (e.g., at 13.56 MHZ), satellite navigations bands (e.g., an L1 global positioning system (GPS) band at 1575 MHz, an L5 GPS band at 1176 MHz, a Global Navigation Satellite System (GLONASS) band, a BeiDou Navigation Satellite System (BDS) band, etc.), ultra-wideband (UWB) communications band(s) supported by the IEEE 802.15.4 protocol and/or other UWB communications protocols (e.g., a first UWB communications band at 6.5 GHZ and/or a second UWB communications band at 8.0 GHZ), and/or any other desired communications bands.

[0058] The radio-frequency transceiver circuitry may include millimeter/centimeter wave transceiver circuitry that supports communications at frequencies between about 10 GHz and 300 GHz. For example, the millimeter/centimeter wave transceiver circuitry may support communications in Extremely High Frequency (EHF) or millimeter wave communications bands between about 30 GHz and 300 GHz and/or in centimeter wave communications bands between about 10 GHz and 30 GHz (sometimes referred to as Super High Frequency (SHF) bands). As examples, the millimeter/centimeter wave transceiver circuitry may support communications in an IEEE K communications band between about 18 GHz and 27 GHz, a K_a communications band between about 26.5 GHZ and 40 GHz, a K_u communications band between about 12 GHZ and 18 GHz, a V communications band between about 40 GHz and 75 GHz, a W communications band between about 75 GHz and 110 GHz, or any other desired frequency band between approximately 10 GHz and 300 GHz. If desired, the millimeter/centimeter wave transceiver circuitry may support IEEE 802.11ad communications at 60 GHz (e.g., WiGig or 60 GHz Wi-Fi bands around 57-61 GHZ), and/or 5^{th} generation mobile networks or 5^{th} generation wireless systems (5G) New Radio (NR) Frequency Range 2 (FR2) communications bands between about 24 GHz and 90 GHz.

[0059] Antennas in wireless communications circuitry **56** may include antennas with resonating elements that are formed from loop antenna structures, patch antenna structures, inverted-F antenna structures, slot antenna structures, planar inverted-F antenna structures, helical antenna structures, dipole antenna structures, monopole antenna structures, hybrids of these designs, etc. Different types of antennas may be used for different bands and combinations of bands. For example, one type of antenna may be used in forming a local wireless link and another type of antenna may be used in forming a remote wireless link antenna.

[0060] During operation, head-mounted device **10** may use communication circuitry **56** to communicate with external equipment **60**. External equipment **60** may include one or more external servers, an electronic device that is paired with head-mounted device **10** (such as a cellular telephone, a laptop computer, a speaker, a computer monitor, an electronic watch, a tablet computer, earbuds, etc.), a vehicle, an internet of things (IoT) device (e.g., remote control, light switch, doorbell, lock, smoke alarm, light, thermostat, oven, refrigerator, stove, grill, coffee maker, toaster, microwave, etc.), etc.

[0061] Electronic device **10** may have housing structures (e.g., housing walls, straps, etc.), as shown by illustrative support structures **62** of FIG. **1**. In configurations in which electronic device **10** is a head-mounted device (e.g., a pair of glasses, goggles, a helmet, a hat, etc.), support structures **62** may include head-mounted support structures (e.g., a helmet housing, head straps, temples in a pair of eyeglasses, goggle housing structures, and/or other head-mounted structures). The head-mounted support structures may be configured to be worn on a head of a user during operation of device **10** and may support control circuitry **14**, input-output circuitry **16**, and/or communication circuitry **56**.

[0062] FIG. **2** is a top view of electronic device **10** in an illustrative configuration in which electronic device **10** is a head-mounted device. As shown in FIG. **2**, electronic device **10** may include support structures (see, e.g., support structures **62** of FIG. **1**) that are used in housing the components of device **10** and mounting device **10** onto a user's head. These support structures may include, for example, structures that form housing walls and other structures for main unit **62-2** (e.g., exterior housing walls, lens module structures, etc.) and eyeglass temples or other supplemental support structures such as structures **62-1** that help to hold main unit **62-2** on a user's face.

[0063] The electronic device may include optical modules such as optical module **70**. The electronic device may include left and right optical modules that correspond respectively to a user's left eye and right eye. An optical module corresponding to the user's left eye is shown in FIG. **2**.

[0064] Each optical module **70** includes a corresponding lens module **72** (sometimes referred to as lens stack-up **72**, lens **72**, or adjustable lens **72**). Lens **72** may include one or more lens elements arranged along a common axis. Each lens element may have any desired shape and may be formed from any desired material (e.g., with any desired refractive index). The lens elements may have unique shapes and refractive indices that, in combination, focus light (e.g., from a display or from the physical environment) in a desired manner. Each lens element of lens module **72** may be formed from any desired material (e.g., glass, a polymer material such as polycarbonate or acrylic, a crystal such as sapphire, etc.).

[0065] Modules **70** may optionally be individually positioned relative to the user's eyes and relative to some of the housing wall structures of main unit **26-2** using positioning circuitry such as positioner **58**. Positioner **58** may include stepper motors, piezoelectric actuators, motors, linear electromagnetic actuators, and/or other electronic components for adjusting the position of displays, the optical modules **70**, and/or lens modules **72**. Positioners **58** may be controlled by control circuitry **14** during operation of device **10**. For example, positioners **58** may be used to adjust the spacing between modules **70** (and therefore the lens-to-lens spacing between the left and right lenses of modules **70**) to match the interpupillary distance IPD of a user's eyes. In another example, the lens module may include an adjustable lens element. The curvature of the adjustable lens element may be adjusted in real time by positioner(s) **58** to compensate for a user's eyesight and/or viewing conditions.

[0066] Each optical module may optionally include a display such as display **18** in FIG. **2**. As previously mentioned, the displays may be omitted from device **10** if desired. In this type of arrangement, the device may still include one or more lens modules **72** (e.g., through which the user views the real world). In this type of arrangement, real-world content may be selectively focused for a user.

[0067] FIG. **3** is a cross-sectional side view of an illustrative lens module with multiple lens elements. As shown, lens module **72** includes a first lens element **72-1** and a second lens element **72-2**. Each surface of the lens elements may have any desired curvature. For example, each surface may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), a combination of convex and concave surfaces, or a freeform surface. A spherically curved surface (e.g., a spherically convex or spherically concave surface) may have a constant radius of curvature across the surface. In contrast, an aspherically curved surface (e.g., an aspheric concave surface or an aspheric convex surface) may have a varying radius of curvature across the surface. A cylindrical surface may only be curved about one axis instead of about multiple axes as with the spherical surface. In some cases, one of the lens surfaces may have an aspheric surface that changes from being convex (e.g., at the center) to concave (e.g., at the edges) at different positions on the surface. This type of surface may be referred to as an aspheric surface, a primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) aspheric surface, a freeform surface, and/or a primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) freeform surface. A freeform surface may include both convex and concave portions and/or curvatures defined by polynomial series and expansions. Alternatively, a freeform surface may have varying convex curvatures or varying concave curvatures (e.g., different portions with different radii of curvature, portions with curvature in one direction and different portions with curvature in two directions, etc.). Herein, a freeform surface that is primarily convex (e.g., the majority of the surface is convex and/or the surface is convex at its center) may sometimes still be referred to as a convex surface and a freeform surface that is primarily concave (e.g., the majority of the surface is concave and/or the surface is concave at its center) may sometimes still be referred to as a concave surface. In one example, shown in FIG. **3**, lens element **72-1** has a convex surface that faces display **18** and an opposing concave surface. Lens element **72-2** has a convex surface that faces lens element **72-1** and an opposing concave surface.

[0068] One or both of lens elements **72-1** and **72-2** may be adjustable. In one example, lens element **72-1** is a non-adjustable lens element whereas lens element **72-2** is an adjustable lens element. The adjustable lens element **72-2** may be used to accommodate a user's eyeglass prescription, for example. The shape of lens element **72-2** may be adjusted if a user's eyeglass prescription changes (without needing to replace any of the other components within device **10**). As another possible use case, a first user with a first eyeglass prescription (or no eyeglass prescription) may use device **10** with lens element **72-2** having a first shape and a second, different user with a second eyeglass prescription may use device **10** with lens element **72-2** having a second shape that is different than the first shape. Lens element **72-2** may have varying lens power and/or may provide varying amounts and orientations of astigmatism correction to provide prescription correction for the user.

[0069] The example of lens module **72** including two lens elements is merely illustrative. In general, lens module **72** may include any desired number of lens elements (e.g., one, two, three, four, more than four, etc.). Any subset or all of the lens elements may optionally be adjustable. Any of the adjustable lens elements in the lens module may optionally be fluid-filled adjustable lenses. Lens module **72** may also include any desired additional optical layers (e.g., partially reflective mirrors that reflect 50% of incident light, linear polarizers, retarders such as quarter wave plates, reflective polarizers, circular polarizers, reflective circular polarizers, etc.) to manipulate light that passes through lens module.

[0070] In one possible arrangement, lens element **72-1** may be a removable lens element. In other words, a user may be able to easily remove and replace lens element **72-1** within optical module **70**. This may allow lens element **72-1** to be customizable. If lens element **72-1** is permanently affixed to the lens assembly, the lens power provided by lens element **72-1** cannot be easily changed. However, by making lens element **72-1** customizable, a user may select a lens element **72-1** that best suits their eyes and place the appropriate lens element **72-1** in the lens assembly. The lens element **72-1** may be used to accommodate a user's eyeglass prescription, for example. A user may replace lens element **72-1** with an updated lens element if their eyeglass prescription changes (without needing to replace any of the other components within electronic device **10**). Lens element **72-1** may have varying lens power and/or may provide varying amount of astigmatism correction to provide prescription correction for the user. Lens element **72-1** may include one or more attachment structures that are configured to attach to corresponding attachment structures included in optical module **70**, lens element **72-2**, support structures **26**, or another structure in electronic device **10**.

[0071] In contrast with lens element **72-1**, lens element **72-2** may not be a removable lens clement. Lens element **72-2** may therefore sometimes be referred to as a permanent lens element, non-removable lens element, etc. The example of lens element **72-2** being a non-removable lens clement is merely illustrative. In another possible arrangement, lens element **72-2** may also be a removable lens element (similar to lens element **72-1**).

[0072] One or more of the adjustable lens elements may be a fluid-filled lens element. An example is described herein where lens element **72-2** from FIG. **3** is a fluid-filled lens element. When lens element **72-2** is a fluid-filled lens element, the lens element may include one or more components that define the surfaces of lens element **72-2**. These elements may also be referred to as lens elements. In other words, adjustable lens element **72-2** (sometimes referred to as adjustable lens module **72-2**, adjustable lens **72-2**, tunable lens **72-2**, etc.) may be formed by multiple respective lens elements.

[0073] FIG. **4** is a cross-sectional side view of adjustable fluid-filled lens element **72-2**. As shown, fluid-filled chamber **82** (sometimes referred to as chamber **82** or fluid chamber **82**) that includes fluid **92** is interposed between lens elements **84** and **86**. Fluid **92** may be a liquid, gel, or gas with a pre-determined index of refraction (and may therefore sometimes be referred to as liquid **92**, gel **92**, or gas **92**). The fluid may sometimes be referred to as an index-matching oil, an optical oil, an optical fluid, an index-matching material, an index-matching liquid, etc. Lens elements **84** and **86** may have the same index of refraction or may have different indices of refraction. Fluid **92** that fills chamber **82** between lens elements **84** and **86** may have an index of refraction that is the same as the index of refraction of lens element **84** but different from the index of refraction of lens element **86**, may have an index of refraction that is the same as the index of refraction of lens element **86** but different from the index of refraction of lens element **84**, may have an index of refraction that is the same as the index of refraction of lens element **84** and lens element **86**, or may have an index of refraction that is different from the index of refraction of lens element **84** and lens element **86**. Lens elements **84** and **86** may have a circular footprint, may have an elliptical footprint, may have or may have a footprint any another desired shape (e.g., an irregular footprint).

[0074] The amount of fluid **92** in chamber **82** may have a constant volume or an adjustable volume. If the amount of fluid is adjustable, the lens module may also include a fluid reservoir and a fluid controlling component (e.g., a pump, stepper motor, piezoelectric actuator, motor, linear electromagnetic actuator, and/or other electronic component that applies a force to the fluid in the fluid reservoir) for selectively transferring fluid between the fluid reservoir and the chamber.

[0075] Lens elements **84** and **86** may be transparent lens elements formed from any desired material (e.g., glass, a polymer material such as polycarbonate or acrylic, a crystal such as sapphire, etc.). Each one of lens elements **84** and **86** may be elastomeric, semi-rigid, or rigid. Elastomeric lens elements may be formed from a natural or synthetic polymer that has a low Young's modulus for high flexibility. For example the elastomeric membrane may be formed from a material having a Young's modulus of less than 1 GPa, less than 0.5 GPa, less than 0.1 GPa, etc.

[0076] Semi-rigid lens elements may be formed from a semi-rigid material that is stiff and solid, but not inflexible. A semi-rigid lens element may, for example, be formed from a thin layer of polymer or glass. Semi-rigid lens elements may be formed from a material having a Young's modulus that is greater than 1 Gpa, greater than 2 GPa, greater than 3 GPa, greater than 10 GPa, greater than 25 GPa, etc. Semi-rigid lens elements may be formed from polycarbonate, polyethylene terephthalate (PET), polymethylmethacrylate (PMMA), acrylic, glass, or any other desired material. The properties of semi-rigid lens elements may result in the lens element becoming rigid along a first axis when the lens element is curved along a second axis perpendicular to the first axis or, more generally, for the product of the curvature along its two principal axes of curvature to remain roughly constant as it flexes. This is in contrast to an elastomeric lens element, which remains flexible along a first axis even when the lens element is curved along a second axis perpendicular to the first axis. The properties of semi-rigid lens elements may allow the semi-rigid lens elements to form a cylindrical lens with tunable lens power and a tunable axis.

[0077] Rigid lens elements may be formed from glass, a polymer material such as polycarbonate or acrylic, a crystal such as sapphire, etc. In general, the rigid lens elements may not deform when pressure is applied to the lens elements within the lens module. In other words, the shape and position of the rigid lens elements may be fixed. Each surface of a rigid lens element may be planar, concave (e.g., spherically, aspherically, or cylindrically concave), or convex (e.g., spherically, aspherically, or cylindrically convex). Rigid lens elements may be formed from a material having a Young's modulus that is greater than greater than 25 GPa, greater than 30 GPa, greater than 40 GPa, greater than 50 GPa, etc.

[0078] One or more structures such as a lens housing **90** (sometimes referred to as housing **90**, lens chassis **90**, chassis **90**, support structure **90**, etc.) may also define the fluid-filled chamber **82** of lens element **72-2**.

[0079] FIG. **5** is a cross-sectional side view of lens element **72-2** showing an illustrative adjustment of the shape of lens element **72-2**. As shown, during adjustments of lens element **72-2**, lens element **84** may be biased in direction **94** at multiple points along its periphery (e.g., a point force is applied in direction **94** at multiple points). In this way, the curvature of the lens element **84** (and accordingly, the lens power of lens element **72-2**) may be adjusted. In one example, the curvature of lens element **84** is adjusted while the curvature of lens element **86** remains constant. Instead or in addition, the lens element **86** may be biased at multiple points along its periphery to adjust the curvature of lens element **86**.

[0080] There are multiple options for how to manipulate the shape of lens element **84**. In one possible arrangement, a plurality of actuators (e.g., linear actuators) may be coupled to the periphery of the lens element. The actuators may be distributed evenly around the periphery of the lens element **84**, as one example. Each actuator (e.g., a linear actuator) may be coupled to a respective portion of lens element **84** and may selectively move that respective portion of lens clement **84** up and down (e.g., in the Z-direction in FIGS. **4** and **5**) to control the position of that respective portion of lens element **84** in the Z-direction. A lens shaping element (e.g., a ring-shaped element) may optionally be coupled to both lens element **84** and the actuators.

[0081] The example of tunable lens element **72-2** being a fluid-filled lens element is merely illustrative. In general, tunable lens element **72-2** may be any desired type of tunable lens element with adjustable optical power.

[0082] A tunable lens element may be incorporated into a number of different types of optical modules. The tunable lens element may be used in virtual reality optical modules (in which an opaque display is viewed through the tunable lens element) and/or augmented reality optical modules (in which the real world is viewed in parallel with display content).

[0083] FIG. **6** is a side view of an optical module **70** with a tunable lens **72-2** and a lens element **72-1** that is non-adjustable. Tunable lens **72-2** may have the arrangement of FIGS. **4** and **5** or any other desired arrangement. The optical module also includes a display **18**. Display **18** may emit light **108** through lens elements **72-1** and **72-2** towards viewer **102** (e.g., a viewer's eye, sometimes referred to as an eye-box). Display **18** may be opaque (e.g., with a transparency that is less than 40%, less than 20%, less than 10%, less than 10%, etc.).

[0084] In FIG. **6**, non-adjustable lens **72-1** has a convex surface **104** and a planar surface **106**. This example is merely illustrative. In general, each surface of the non-adjustable lens **72-1** may have any desired shape. The non-adjustable lens **72-1** may be formed from a single piece of glass or plastic, as examples.

[0085] In FIG. **6**, lens element **72-1** is interposed between display **18** and tunable lens **72-2**. This example is merely illustrative and lens elements **72-1** and **72-2** may be switched if desired (e.g., such that tunable lens element **72-2** is interposed between non-adjustable lens element **72-1** and display **18**).

[0086] The non-adjustable lens element **72-1** in FIG. **6** may magnify the images from display **18** for viewer **102**. In other words, non-adjustable lens element **72-1** may have a positive optical power that is fixed. Tunable lens **72-2** may be adjusted between any desired optical powers. The optical power of tunable lens **72-2** may be adjusted between different negative optical powers, may be adjusted between different positive optical powers, or may be adjusted between both positive and negative optical powers.

[0087] The example in FIG. **6** of a single non-adjustable lens element **72-1** being included is merely illustrative. In general, one or more non-adjustable lens elements may be included. For example, two non-adjustable lens elements that are collectively referred to as a doublet may be included, three non-adjustable lens elements that are collectively referred to as a triplet may be included, etc.

[0088] In another possible arrangement, shown in FIG. **7**, the non-adjustable lens element **72-1** may be omitted from optical module **70**. As shown in FIG. **7**, tunable lens element **72-2** is the only lens element between display **18** and viewer **102**. Tunable lens **72-2** may have the arrangement of FIGS. **4** and **5** or any other desired arrangement. Display **18** may emit light **108** through lens element **72-2** towards viewer **102**. Display **18** may be opaque (e.g., with a transparency that is less than 40%, less than 20%, less than 10%, less than 10%, etc.).

[0089] The adjustable lens element **72-2** in FIG. **7** may magnify the images from display **18** for viewer **102**. In other words, the optical power of tunable lens **72-2** may be adjusted between different positive optical powers.

[0090] FIG. **8** is a side view of an optical module **70** with a tunable lens **72-2** and a Fresnel lens element **72-1** that is non-adjustable. Tunable lens **72-2** may have the arrangement of FIGS. **4** and **5** or any other desired arrangement. The optical module also includes a display **18**. Display **18** may emit light **108** through lens elements **72-1** and **72-2** towards viewer **102** (e.g., a viewer's eye, sometimes referred to as an eye-box). Display **18** may be opaque (e.g., with a transparency that is less than 40%, less than 20%, less than 10%, less than 10%, etc.).

[0091] In FIG. **8**, non-adjustable lens **72-1** is a Fresnel lens. Fresnel lens **72-1** is characterized by slope facets **110** and draft facets **114**. Facets **110** and **114** are formed from the surfaces of ring-shaped Fresnel lens portions such as concentric Fresnel lens rings **112**. There may be any suitable number of rings **112** in Fresnel lens **72-1** (e.g., 50, 10-100, at least 5, at least 10, at least 15, at least 20, at least 30, at least 45, at least 75, fewer than 200, fewer than 150, or other suitable number). Slope facets **110** have a curved lens-shaped profile and exhibit relatively small angles (e.g., less than 45°, less than 30°, less than 20°, 0-20°, 0-30°, 0-40°, at least 2°, etc.) with respect to lateral dimensions such as the X-axis. Draft facets **114**, which may have straight cross-sectional profiles, typically have relatively small angles (e.g., 2°) with respect to the Z-axis. The Z-axis is normal to the plane of the surface of lens **72-1** and is therefore orthogonal to the X-axis. The Z-axis may be referred to as the optical axis of the lens and may be referred to as a vertical dimension. Because of these orientations, draft facets **114** may sometimes be referred to as vertically extending facets and slope facets **110** may sometimes be referred to as horizontally extending or laterally extending facets (where the angle is less than 45 degrees from the plane of the lens). Fresnel lens element **72-1** may be formed from a single piece of glass or plastic, as examples.

[0092] In FIG. **8**, Fresnel lens element **72-1** is interposed between display **18** and tunable lens **72-2**. This example is merely illustrative and lens elements **72-1** and **72-2** may be switched if desired (e.g., such that tunable lens element **72-2** is interposed between Fresnel lens element **72-1** and display **18**).

[0093] The Fresnel lens element **72-1** in FIG. **8** may magnify the images from display **18** for viewer **102**. In other words, Fresnel lens element **72-1** may have a positive optical power that is fixed. Tunable lens **72-2** may be adjusted between any desired optical powers. The optical power of tunable lens **72-2** may be adjusted between different negative optical powers, may be adjusted between different positive optical powers, or may be adjusted between both positive and negative optical powers.

[0094] In another possible arrangement, shown in FIG. **9**, the Fresnel lens element **72-1** may be integrated with tunable lens element **72-2**. As shown in FIG. **9**, Fresnel lens element **72-1** may be formed in direct contact with lens element **86** that defines a fluid-filled chamber **82** for tunable lens element **72-2**. In other words, lens element **86** has a first side that is in direct contact with Fresnel lens element **72-1** and a second, opposing side that is in direct contact with fluid **92** in fluid-filled chamber **82**.

[0095] If desired, lens element **86** may be omitted and Fresnel lens element **72-1** may define a fluid-filled chamber **82** for tunable lens element **72-2**. In other words, Fresnel lens element **72-1** may be in direct contact with fluid **92** in fluid-filled chamber **82**. The Fresnel lens element **72-1** may have a first side with Fresnel rings **112** and a second, opposing side that is planar. The planar side of the Fresnel lens element may be in direct contact with lens element **86** (or fluid **92** if lens element **86** is omitted).

[0096] FIG. **10** is a side view of an optical module **70** with a tunable lens **72-2** and a catadioptric lens element **72-1** that is non-adjustable. Tunable lens **72-2** may have the arrangement of FIGS. **4** and **5** or any other desired arrangement. The optical module also includes a display **18**. Display **18** may emit light **108** through lens elements **72-1** and **72-2** towards viewer **102** (e.g., a viewer's eye, sometimes referred to as an eye-box). Display **18** may be opaque (e.g., with a transparency that is less than 40%, less than 20%, less than 10%, less than 10%, etc.).

[0097] In general, catadioptric lens **72-1** may include optical structures such as partially reflective coatings, wave plates, reflective polarizers, linear polarizers, antireflection coatings, cholesteric liquid crystal layers, and/or other optical components. These optical structures may allow light rays from display **18** to pass through and/or reflect from surfaces in lens **72-1**, thereby providing a desired lens power. In FIG. **10**, non-adjustable lens **72-1** includes lens elements **120** and **126**, a reflective polarizer **122**, a quarter wave plate **124**, and a partially reflective layer **128**.

[0098] As shown in FIG. **10**, a partially reflective mirror (e.g., a metal mirror coating or other mirror coating such as a dielectric multilayer coating with a 50% transmission and a 50% reflection) such as partially reflective mirror **128** may be formed on the convex surface of lens clement **126**. Partially reflective mirror **128** may sometimes be referred to as beam splitter **128**, half mirror (HM) **128**, partially reflective layer **128**, etc. Partially reflective layer **128** may have a reflectance that is greater than 20%, greater than 40%, less than 80%, less than 60%, between 40% and 60%, etc.

[0099] A wave plate such as wave plate **124** may be formed on the concave surface of lens element **126**. Wave plate **124** may be attached to lens element **126** (e.g., using an optically clear adhesive layer or via coating directly to the lens element without an intervening adhesive layer). Wave plate **124** (sometimes referred to as retarder **124**, quarter wave plate (QWP) **124**, etc.) may be a quarter wave plate that conforms to the concave surface of lens element **126**. Retarder **124** may be a coating on the concave surface of lens element **126**.

[0100] Reflective polarizer **122** may be attached to retarder **124** (e.g., using an optically clear adhesive layer or via coating directly to the retarder without an intervening adhesive layer). Reflective polarizer **122** may have orthogonal reflection and pass axes. Light that is polarized parallel to the reflection axis of reflective polarizer **122** will be reflected by reflective polarizer **122**. Light that is polarized perpendicular to the reflection axis and therefore parallel to the pass axis of reflective polarizer **122** will pass through reflective polarizer **122**. Reflective polarizer **122** may sometimes be referred to as an advanced polarization film (APF).

[0101] As shown in FIG. **10**, light **108** from display **18** may pass through partially reflective layer **128**, lens element **126**, and quarter wave plate **124** in that order before being reflected by reflective polarizer **122**. The light reflected by reflective polarizer **122** passes through quarter wave plate **124** and lens element **126** in that order before being reflected by partially reflective layer **128**. The light reflected by partially reflective layer **128** then passes through lens element **126**, quarter wave plate **124**, reflective polarizer **122**, lens element **120**, and tunable lens element **72-2** in that order to reach viewer **102**.

[0102] In the example of FIG. **10**, lens element **126** has one convex surface and one concave surface whereas lens element **120** has two convex surfaces. This example is merely illustrative and in general each surface of each lens element may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), or a freeform surface. Different surfaces of the same lens element may have different radii of curvature. Different surfaces of different lens elements may have different radii of curvature. Each one of lens elements **120** and **126** may be formed from a transparent material such as plastic or glass.

[0103] Additional optical layers may be incorporated into catadioptric lens element **72-1** if desired. As a specific example, a linear polarizer may be included (e.g., between lens element **120** and tunable lens element **72-2** or between reflective polarizer **122** and lens element **120**).

[0104] In FIG. **10**, catadioptric lens element **72-1** is interposed between display **18** and tunable lens **72-2**. This example is merely illustrative and lens elements **72-1** and **72-2** may be switched if desired (e.g., such that tunable lens element **72-2** is interposed between catadioptric lens clement **72-1** and display **18**).

[0105] The catadioptric lens element **72-1** in FIG. **10** may magnify the images from display **18** for viewer **102**. In other words, catadioptric lens element **72-1** may have a positive optical power that is fixed. Tunable lens **72-2** may be adjusted between any desired optical powers. The optical power of tunable lens **72-2** may be adjusted between different negative optical powers, may be adjusted between different positive optical powers, or may be adjusted between both positive and negative optical powers.

[0106] In the example of FIG. **10**, catadioptric lens element **72-1** includes two lens elements. This example is merely illustrative. Lens element **120** may be omitted from the catadioptric lens element of FIG. **10** if desired. Alternatively, the catadioptric lens element **72-1** may include three lens elements. FIG. **11** shows an example where catadioptric lens element **72-1** includes lens element **130** in addition to lens elements **120** and **126**. Lens element **130** is interposed between partially reflective layer **128** and display **18**. The other components in catadioptric lens **72-1** of FIG. **11** are otherwise the same as in FIG. **10**.

[0107] In the example of FIG. **11**, lens element **130** has one convex surface and one concave surface. This example is merely illustrative and in general each surface of lens element **130** may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), or a freeform surface. Different surfaces of lens element **130** may have different radii of curvature. Lens elements **130** may be formed from a transparent material such as plastic or glass.

[0108] In FIG. **11**, as in FIG. **10**, tunable lens element **72-2** may instead be interposed between catadioptric lens **72-1** and display **18** if desired.

[0109] In FIGS. **10** and **11**, quarter wave plate **124** may alternatively be positioned between lens element **126** and partially reflective layer **128**.

[0110] In yet another possible arrangement, shown in FIG. **12**, the catadioptric lens **72-1** may be a dialyte-type catadioptric lens with an air gap **132** between lens elements **120** and **126**. The function of catadioptric lens **72-1** in FIG. **12** is otherwise the same as the catadioptric lens in FIG. **10**. In FIG. **12**, reflective polarizer **122** is formed on lens element **120** between lens element **120** and quarter wave plate **124** and quarter wave plate **124** is formed on lens element **126** between reflective polarizer **122** and lens element **126**. This example is merely illustrative. The reflective polarizer may instead be formed on lens element **126** if desired. Similarly, the quarter wave plate **124** may instead be formed on lens element **120** if desired. The quarter wave plate **124** may instead be formed between lens element **126** and partially reflective layer **128** if desired.

[0111] In FIG. **12**, as in FIG. **10**, tunable lens element **72-2** may instead be interposed between catadioptric lens **72-1** and display **18** if desired.

[0112] In another possible arrangement, one or more non-adjustable lenses in a catadioptric lens may be replaced with a tunable lens. For example, any of lens elements **120**, **126**, and **130** in FIGS. **10-12** may be replaced with tunable lens element **72-2** if desired. FIG. **13** is a side view of one example in which non-adjustable lens **126** from FIG. **10** has been replaced with tunable lens **72-2**.

[0113] As shown in FIG. **13**, catadioptric lens **140** includes lens element **120**, reflective polarizer **122**, quarter wave plate **124**, tunable lens element **72-2**, and partially reflective layer **128**. Tunable lens **72-2** may have the arrangement of FIGS. **4** and **5** or any other desired arrangement.

[0114] Quarter wave plate **124** may be in direct contact with lens element **86** of lens element **72-2**. This example is merely illustrative. If desired, lens element **86** may be omitted and quarter wave plate **124** may define fluid-filled chamber **82** and directly contact fluid **92**. In other words, in FIG. **13** quarter wave plate **124** has a first side that directly contacts reflective polarizer **122** and a second, opposing side that directly contacts lens element **86** of tunable lens element **72-2**. Alternatively, quarter wave plate **124** may have a first side that directly contacts reflective polarizer **122** and a second, opposing side that directly contacts fluid **92** of tunable lens element **72-2**.

[0115] Partially reflective layer **128** may be in direct contact with lens element **84** of lens element **72-2**. This example is merely illustrative. If desired, lens element **84** may be omitted and partially reflective layer **128** may define fluid-filled chamber **82** and directly contact fluid **92**. In other words, in FIG. **13** partially reflective layer **128** has a first side that faces display **18** and a second, opposing side that directly contacts lens element **84** of tunable lens element **72-2**. Alternatively, partially reflective layer **128** may have a first side that faces display **18** and a second, opposing side that directly contacts fluid **92** of tunable lens element **72-2**.

[0116] As shown in FIG. **13**, light **108** from display **18** may pass through partially reflective layer **128**, lens element **84**, fluid **82**, lens element **86**, and quarter wave plate **124** in that order before being reflected by reflective polarizer **122**. The light reflected by reflective polarizer passes through quarter wave plate **124**, lens element **86**, fluid **82**, and lens element **84** in that order before being reflected by partially reflective layer **128**. The light reflected by partially reflective layer **128** then passes through lens element **84**, fluid **82**, lens element **86**, quarter wave plate **124**, reflective polarizer **122**, and lens element **120** in that order to reach viewer **102**. In other words, the light may make multiple passes through tunable lens **72-2** before reaching viewer **102**.

[0117] In FIG. **13**, the shape of lens element **84** in tunable lens **72-2** may be adjusted. This example is merely illustrative. If desired, the shape of lens element **86** in tunable lens **72-2** may be adjusted instead or in addition to the shape of lens element **84**.

[0118] When a tunable lens element is used in a catadioptric lens, any of the optical layers described herein may optionally define the fluid-filled chamber of the tunable lens element and may directly contact the fluid in the tunable lens element. For example, reflective polarizer **122** may directly contact the fluid in the tunable lens element if lens element **120** is replaced with a tunable lens element. An optional linear polarizer in the catadioptric lens may directly contact the fluid in the tunable lens element if desired.

[0119] For each one of FIGS. **10-13**, the lens module may collectively be referred to as a catadioptric lens module **72** due to the optical components in the lens module causing both refraction and reflection of light.

[0120] FIG. **14** is a side view of an optical module with a birdbath architecture that includes a tunable lens. As shown in FIG. **14**, optical module **70** includes a display **18**, tunable lens **72-2**, a partially reflective layer **146**, and a reflective layer **148**.

[0121] Display **18** may emit light **108** through lens elements **72-2** towards partially reflective layer **146**. Display **18** may be opaque (e.g., with a transparency that is less than 40%, less than 20%, less than 10%, less than 10%, etc.).

[0122] Partially reflective mirror **146** (e.g., a metal mirror or other mirror) may sometimes be referred to as beam splitter **146**, half mirror (HM) **146**, partially reflective layer **146**, etc. Partially reflective layer **146** may have a reflectance that is greater than 20%, greater than 40%, less than 80%, less than 60%, between 40% and 60%, etc.

[0123] Reflective layer **148** may have a reflectance that is greater than 80%, greater than 90%, greater than 95%, greater than 99%, etc. Reflective layer 148 may have a surface with concave curvature that receives light **108** from display **18** through tunable lens **72-2** and partially reflective layer **146** and reflects the light back towards the partially reflective layer. The light reflected by reflective layer **148** may then reflect off partially reflective layer **146** towards viewer **102**.

[0124] As shown in FIG. **14**, the viewer may also receive light **144** from a physical object **142** in the viewer's physical environment. Light **144** may pass through partially reflective layer **146** to reach viewer **102**.

[0125] In FIG. **14**, tunable lens **72-2** focuses light from display **18** without focusing real world light **144** from the viewer's physical environment. This example is merely illustrative and tunable lens **72-2** may optionally focus the real world light **144** instead or in addition to the light from display **18**. In general, tunable lens **72-2** may be positioned at any point within the optical path of light **108** and/or light **144**. For example, the tunable lens **72-2** may be interposed between partially reflective layer **146** and reflective layer **148**. In this case, the light may make multiple passes through the tunable lens.

[0126] In another possible arrangement, shown in FIG. **15**, optical module **70** may include a display **18**, tunable lens **72-2**, and partially reflective layer **146**. Display **18** may emit light **108** through lens elements **72-2** towards partially reflective layer **146**. Display **18** may be opaque (e.g., with a transparency that is less than 40%, less than 20%, less than 10%, less than 10%, etc.). Partially reflective mirror **146** (e.g., a metal mirror or other mirror) may sometimes be referred to as beam splitter **146**, half mirror (HM) **146**, partially reflective layer **146**, etc. Partially reflective layer **146** may have a reflectance that is greater than 20%, greater than 40%, less than 80%, less than 60%, between 40% and 60%, etc. Partially reflective layer **146** may have curved surfaces if desired.

[0127] Light **108** therefore passes through tunable lens **72-2** and is reflected by partially reflective layer **146** towards viewer **102**. As shown in FIG. **15**, the viewer may also receive light **144** from a physical object **142** in the viewer's physical environment. Light **144** may pass through partially reflective layer **146** to reach viewer **102**.

[0128] In each one of FIGS. **14** and **15**, tunable lens **72-2** may be adjusted between different negative optical powers, may be adjusted between different positive optical powers, or may be adjusted between both positive and negative optical powers.

[0129] A tunable lens may be incorporated into an optical module that includes a waveguide. Examples of this type are shown in FIGS. **16-18**. The optical module may include an input coupler **158**, a waveguide **152**, an output coupler **160**, a negative bias lens **154**, a tunable positive bias lens **72-2**, and a cover layer **156**.

[0130] Display **18** may be used to create an image for viewer **102** (e.g., eye **102**). Display **18** may be formed by a digital mirror device, a liquid-crystal-on-silicon device, a scanning microelectromechanical systems mirror device, another reflective display device, or any other display type.

[0131] Input coupler **158** (e.g., prisms, holograms, etc.) may be used to couple images from display **18** into waveguide **152**. Light **108** from the images may be guided within waveguide **152** in accordance with the principal of total internal reflection. In this way, the image may be transported from the side of device **10** towards the center of device **10** (e.g., in the negative Z-direction in FIG. **16**) to a position that is aligned with the viewer's eye **102**. Waveguide **152** may be provided with an output coupler **160** such as holograms formed on or in the material of waveguide **152**. The output coupler **160** may couple the images from the waveguide **152** towards the viewer. This allows a user to view a computer-generated image (display image) overlaid over real-world objects such as real-world object **142**. In other words, the viewer receives both light **108** from display **18** (via waveguide **152**) and light **144** from physical objects such as physical object **142**.

[0132] Tunable positive bias lens **72-2** may be interposed between the front (outwardly facing) side of device **10** and waveguide **152** (e.g., between real-world object **142** and waveguide **152**). Tunable positive bias lens **72-2** may apply a positive optical power to light traveling in the negative Z-direction. Negative bias lens **154** may be interposed between waveguide **152** and the rear (inwardly facing) side of device **10** (e.g., between waveguide **152** and viewer **102**). Negative bias lens **154** may apply a negative optical power to light traveling in the negative Z-direction.

[0133] Tunable lens **72-2** may have the arrangement of FIGS. **4** and **5** or any other desired arrangement. In FIG. **16**, tunable lens **72-2** is formed directly adjacent to cover layer **156**. Cover layer **156** may be formed from glass or plastic. Cover layer **156** may have first and second opposing surfaces, with the first surface forming an exterior surface of device **10** and the second surface directly contacting tunable lens **72-2**.

[0134] In FIG. **16**, the curvature of lens element **84** may be adjusted in tunable lens **72-2**. In one possible arrangement, shown in FIG. **16**, cover layer **156** directly contacts lens element **86** of tunable lens **72-2**. In other words, lens element **86** has a first side that directly contacts cover layer **156** and a second, opposing side that partially defines fluid-filled chamber **82** and directly contacts fluid **92**. Alternatively, lens element **86** may be omitted and cover layer **156** may partially define fluid-filled chamber **82** and directly contact fluid **92**.

[0135] In some situations, the powers of bias lenses **154** and **72-2** may be complementary. For example, bias lens **72-2** may have a positive lens power such as 1.5 diopter and bias lens **154** may have a negative lens power such as a −1.5 diopter. With this type of arrangement, the positive power of lens **72-2** is cancelled by the corresponding negative power of lens **154**, so that the net effect is as if there were no lens present between the real-world objects and viewer **102** (e.g., real-world image experiences a zero lens power from lenses **72-2** and **154** when traveling to viewer **102**). At the same time, the negative power of lens **154** is applied to the images from display **18** that exit waveguide **152** and travel through lens **154** to reach viewer **102**.

[0136] Tunable lens **72-2** may be adjusted between different negative optical powers, may be adjusted between different positive optical powers, or may be adjusted between both positive and negative optical powers. When tunable lens **72-2** is set to a positive optical power of the same magnitude as the negative optical power applied by negative bias lens **154**, the net optical power applied to the real world light by lenses **72-2** and **154** is 0. When tunable lens **72-2** is set to a positive optical power of a lower magnitude than the negative optical power applied by negative bias lens **154**, the net optical power applied to the real world light by lenses **72-2** and **154** is negative. When tunable lens **72-2** is set to a negative optical power, the net optical power applied to the real world light by lenses **72-2** and **154** is negative. When tunable lens **72-2** is set to a positive optical power of a higher magnitude than the negative optical power applied by negative bias lens **154**, the net optical power applied to the real world light by lenses **72-2** and **154** is positive.

[0137] In this way, tunable lens **72-2** in FIG. **16** may be adjusted to selectively focus the real world image light **144** (e.g., from physical object **142**).

[0138] FIG. **16** shows how one or more components in the optical module may be coupled to support structures **62**. Support structures **62** may be coupled to any of the components in any of the optical modules of FIGS. **6-18**.

[0139] In the example of FIG. **16**, adjustable positive bias lens **72-2** is formed adjacent to cover layer **156**. Alternatively, as shown in FIG. **17**, there may be an air gap between tunable lens **72-2** and cover layer **156**. The arrangement of FIG. **17** is otherwise the same as the arrangement of FIG. **16**.

[0140] In the example of FIGS. **16** and **17**, negative bias lens **154** is non-adjustable whereas the positive bias lens is formed using tunable lens **72-2**. The opposite arrangement may instead be used if desired, with an adjustable negative bias lens used in the same optical module as a non-adjustable positive bias lens.

[0141] Alternatively, as shown in FIG. **18**, the optical module **70** may include both an adjustable negative bias lens **154** and an adjustable positive bias lens **72-2**. Each one of adjustable negative bias lens **154** and adjustable positive bias lens **72-2** may have the arrangement of tunable lens **72-2** in FIGS. **4** and **5** or any other desired arrangement.

[0142] In FIG. **18**, adjustable negative bias lens **154** includes a fluid-filled chamber **82** defined by lens elements **84** and **86** that is filled with fluid **92** and that includes lens housing structures **90**. Adjustable negative bias lens **154** in FIG. **18** additionally includes a fixed (non-adjustable) lens element **154**-F with a concave curved surface. Fixed lens element **154**-F may be formed from a single piece of plastic or glass, as examples.

[0143] In one example, adjustable negative bias lens **154** may be adjusted between different negative optical powers whereas adjustable positive bias lens **72-2** may be adjusted between different positive optical powers.

[0144] Adjustable negative bias lens **154** and adjustable positive bias lens **72-2** may be controlled individually (e.g., by control circuitry **14**) in one possible embodiment. In other words, the adjustable negative bias lens **154** may be adjusted to change the optical power provided by adjustable negative bias lens **154** without changing the optical power provided by adjustable positive bias lens **72-2**. Similarly, the adjustable positive bias lens **72-2** may be adjusted to change the optical power provided by adjustable positive bias lens **72-2** without changing the optical power provided by adjustable negative bias lens **154**.

[0145] Alternatively, there may optionally be a channel such as channel **162** that connects the fluid-filled chamber for adjustable negative bias lens **154** with the fluid-filled chamber for adjustable positive bias lens **72-2**. When channel **162** is included, fluid may move between the two chambers through the channel. When channel **162** is included, controlling a single adjustable lens element in either one of lenses **154** and **72-2** may change the shape of both the adjustable negative bias lens **154** and adjustable positive bias lens **72-2**. In other words, the adjustable negative bias lens and the adjustable positive bias lens are adjusted synchronously.

[0146] For example, adjusting the shape of lens element **84** in adjustable positive bias lens **72-2** may, in addition to changing the shape (and optical power of) adjustable positive bias lens **72-2**, change the shape (and optical power of) adjustable negative bias lens **154** (more specifically lens element **84** in adjustable negative bias lens **154**). The opposite arrangement may also be used, with adjusting the shape of lens element **84** in adjustable negative bias lens **154** also changing the shape (and optical power of) adjustable positive bias lens **72-2** (more specifically lens element **84** in adjustable positive bias lens **72-2**).

[0147] FIG. **19** is a side view of an optical module **70** with a lens module that includes a tunable lens **72-2** and a catadioptric lens element **72-1** that is non-adjustable. Tunable lens **72-2** may have the arrangement of FIGS. **4** and **5** or any other desired arrangement. The optical module also includes a display **18**. Display **18** may emit light through lens elements **72-1** and **72-2** towards viewer **102** (e.g., a viewer's eye, sometimes referred to as an eye-box). Display **18** may be opaque (e.g., with a transparency that is less than 40%, less than 20%, less than 10%, less than 10%, etc.).

[0148] In the example of FIG. **19**, catadioptric lens **72-1** includes lens elements **120** and **126**, a partially reflective layer **128** between lens elements **120** and **126**, a quarter wave plate **124** between lens element **120** and partially reflective layer **128**, and a reflective polarizer **122**. These optical structures may allow light rays from display **18** to pass through and/or reflect from surfaces in lens **72-1**, thereby providing a desired lens power. FIG. **19** shows a path for light **108** that is emitted by display **18** in the negative Z-direction, passes through partially reflective layer **128**, reflects off reflective polarizer **122** in the positive Z-direction, reflects off partially reflective layer **128** in the negative Z-direction, and then passes through reflective polarizer **122** in the negative Z-direction.

[0149] In the example of FIG. **19**, lens element **126** has a convex surface that faces display **18** and a concave surface that faces viewer **102** and lens element **120** has a convex surface that faces display **18** and a concave surface that faces viewer **102**. As shown in FIG. **19**, a partially reflective mirror (e.g., a metal mirror coating or other mirror coating such as a dielectric multilayer coating with a 50% transmission and a 50% reflection) such as partially reflective mirror **128** may be formed on the concave surface of lens element **126**. Partially reflective mirror **128** may sometimes be referred to as beam splitter **128**, half mirror (HM) **128**, partially reflective layer **128**, etc. Partially reflective layer **128** may have a reflectance that is greater than 20%, greater than 40%, less than 80%, less than 60%, between 40% and 60%, etc.

[0150] A wave plate such as wave plate **124** may be formed on the convex surface of lens clement **120** between lens clement **120** and partially reflective layer **128**. Wave plate **124** may be attached to lens element **120** (e.g., using an optically clear adhesive layer or via coating directly to the lens element without an intervening adhesive layer). Wave plate **124** (sometimes referred to as retarder **124**, quarter wave plate (QWP) **124**, etc.) may be a quarter wave plate that conforms to the convex surface of lens element **120**. Retarder **124** may be a coating on the convex surface of lens element **120**. These examples are merely illustrative and wave plate **124** may instead optionally be attached or coated to the concave surface of lens element **120**.

[0151] Reflective polarizer **122** may be attached to the concave surface of lens element **120**. Reflective polarizer **122** may have orthogonal reflection and pass axes. Light that is polarized parallel to the reflection axis of reflective polarizer **122** will be reflected by reflective polarizer **122**. Light that is polarized perpendicular to the reflection axis and therefore parallel to the pass axis of reflective polarizer **122** will pass through reflective polarizer **122**. Reflective polarizer **122** may sometimes be referred to as an advanced polarization film (APF).

[0152] In the example of FIG. **19**, lens elements **120** and **126** each have one convex surface and one concave surface. This example is merely illustrative and in general each surface of each lens clement may be a convex surface (e.g., a spherically convex surface, a cylindrically convex surface, or an aspherically convex surface), a concave surface (e.g., a spherically concave surface, a cylindrically concave surface, or an aspherically concave surface), or a freeform surface. Different surfaces of the same lens element may have different radii of curvature. Different surfaces of different lens elements may have different radii of curvature. Each one of lens elements **120** and **126** may be formed from a transparent material such as plastic or glass.

[0153] Additional optical layers may be incorporated into catadioptric lens element **72-1** if desired. As a specific example, a linear polarizer may be included (e.g., between reflective polarizer **122** and tunable lens element **72-2**).

[0154] In FIG. **19**, catadioptric lens element **72-1** is interposed between display **18** and tunable lens **72-2**. This example is merely illustrative and lens elements **72-1** and **72-2** may be switched if desired (e.g., such that tunable lens element **72-2** is interposed between catadioptric lens element **72-1** and display **18**).

[0155] The catadioptric lens element **72-1** in FIG. **19** may magnify the images from display **18** for viewer **102**. In other words, catadioptric lens element **72-1** may have a positive optical power that is fixed. Tunable lens **72-2** may be adjusted between any desired optical powers. The optical power of tunable lens **72-2** may be adjusted between different negative optical powers, may be adjusted between different positive optical powers, or may be adjusted between both positive and negative optical powers.

[0156] In the example of FIG. **19**, tunable lens **72-2** has a lens element **86** with an aspheric concave surface **S1**. The curvature of surface SI may be fixed. Tunable lens **72-2** also has a lens element **84** with a convex surface **S2** that has adjustable curvature. Adjusting the curvature of surface **S2**

of the tunable lens **72-2** may set the total optical power of optical module **70** within a range of −6 Diopters and +3 Diopters (as one example).

[0157] In another embodiment, shown in FIG. **20**, tunable lens **72-2** may be incorporated into a catadioptric lens module with multiple lens elements. As shown in FIG. **20**, optical module **70** includes a tunable lens **72-2** that is interposed between lens elements **120** and **126**. Lens element **126** has a convex surface that faces display **18** and a concave surface that faces viewer **102**. Lens element **120** has a convex surface that faces display **18** and a concave surface that faces viewer **102**. Tunable lens **72-2** has a lens element **86** with an aspheric concave surface S**1**. The curvature of surface S**1** may be fixed. Tunable lens **72-2** also has a lens element **84** with a convex surface S**2** that has adjustable curvature.

[0158] In the example of FIG. **20**, partially reflective layer **128** is formed on the convex surface of lens element **126** and reflective polarizer **122** is formed on the concave surface SI of lens element **86** in tunable lens **72-2**. A quarter wave plate **124** is interposed between lens element **126** and partially reflective layer **128**. The location of the quarter wave plate in FIG. **20** is merely illustrative. The quarter wave plate may alternatively be formed on the concave surface of lens element **126**, on the convex surface S**2** of tunable lens **72-2**, or on the concave surface S**1** of tunable lens **72-2**.

[0159] FIG. **20** further shows how there may be an air gap **302** between tunable lens **72-2** and lens element **126**. FIG. **20** shows a path for light **108** that is emitted by display **18** in the negative Z-direction, passes through partially reflective layer **128**, lens element **126**, air gap **302**, and tunable lens **72-2**, reflects off reflective polarizer **122** in the positive Z-direction, passes through tunable lens **72-2**, air gap **302**, and lens element **126**, reflects off partially reflective layer **128** in the negative Z-direction, and then passes through lens element **126**, air gap **302**, tunable lens **72-2**, reflective polarizer **122**, and lens clement **120** in the negative Z-direction. The light therefore makes three passes through tunable lens **72-2** between being emitted by display **18** and reaching viewer **102**. This effectively triples the optical power provided by adjustable surface S**2** in tunable lens **72-2**, allowing for the total thickness of tunable lens **72-2** to be mitigated while achieving a target optical power range for optical module **70**.

[0160] FIG. **20** shows how further control of the shape of surface S**2** in tunable lens **72-2** may be achieved by adjusting the amount of fluid **92** in fluid-filled chamber **82**. As shown in FIG. **20**, a fluid control component **304** may be connected between fluid-filled chamber **82** and a fluid reservoir **306** that includes additional fluid **92**. The fluid control component **304** may adjust the volume of fluid **92** that is included in fluid-filled chamber **82**. Adjusting the amount of volume in the fluid-filled chamber may change the curvature of surface S**2**.

[0161] There may be one or more fluid channels between fluid-filled chamber **82** and reservoir **306** that allow fluid control component **304** to control the amount of fluid in fluid-filled chamber **82**. Fluid control component **304** may be a pump, stepper motor, piezoelectric actuator, shape memory alloy (SMA), motor, hydraulic actuator, linear electromagnetic actuator, and/or other electronic component that applies a force to the fluid **92**.

[0162] As one example, the magnitude of the fluid in fluid-filled chamber **82** may be used to adjust a spherical optical power provided by tunable lens **72-2** and edge actuation along a periphery of the tunable lens may be used to adjust a cylindrical optical power provided by tunable lens **72-2**.

[0163] In the example of FIG. **20**, there may be an air gap between tunable lens **72-2** and lens element **126** as well as an air gap between tunable lens **72-2** and lens element **120**. This example is merely illustrative and one or both of these air gaps may be omitted if desired (e.g., tunable lens **72-2** may be directly bonded to lens elements **120** and/or **126** or there may be a low-index filler between tunable lens **72-2** and lens elements **120** and/or **126**).

[0164] FIGS. **21**A and **21**B show an optical module where the amount of fluid in a fluid-filled chamber of a tunable lens is used to adjust the spherical optical power of the lens module. As shown in FIG. **21**A, optical module **70** may include a tunable lens **72-2** that is interposed between lens elements **126** and **120**. Lens element **126** has a convex surface that faces display **18** and a concave surface that faces viewer **102**. Lens element **120** has a convex surface that faces display **18** and a concave surface that faces viewer **102**. Tunable lens **72-2** has a lens element **86** with an aspheric concave surface S**1**. The curvature of surface SI may be fixed. Tunable lens **72-2** also has a lens element **84** with a convex surface S**2**.

[0165] In the examples of FIGS. **21**A and **21**B, partially reflective layer **128** is formed on the concave surface of lens element **126** and reflective polarizer **122** is formed on the concave surface S**1** of lens element **86** in tunable lens **72-2**. A quarter wave plate **124** is interposed between partially reflective layer **128** and lens element **84**. The location of the quarter wave plate in FIGS. **21**A and **21**B is merely illustrative. The quarter wave plate may alternatively be formed on the concave surface of lens element **86**.

[0166] In FIGS. **21**A and **21**B, the amount of fluid in fluid-filled chamber **82** may be adjusted to change the spherical power provided by the tunable lens. As shown in FIG. **21**A, a fluid control component **304** may be connected between fluid-filled chamber **82** and a fluid reservoir **306** that includes additional fluid **92**. The fluid control component **304** may adjust the volume of fluid **92** that is included in fluid-filled chamber **82**. There may be one or more fluid channels between fluid-filled chamber **82** and reservoir **306** that allow fluid control component **304** to control the amount of fluid in fluid-filled chamber **82**. Fluid control component **304** may be a pump, stepper motor, piezoelectric actuator, shape memory alloy (SMA), motor, hydraulic actuator, linear electromagnetic actuator, and/or other electronic component that applies a force to the fluid **92**.

[0167] Adjusting the amount of volume in the fluid-filled chamber may change the thickness of fluid-filled chamber **82**. In FIG. **21**A, the fluid-filled chamber has a first thickness **308-1** that is associated with a minimum spherical optical power (e.g., −10.5 Diopters). In FIG. **21**B, the fluid control component **304** has pumped additional fluid **92** from reservoir **306** into chamber **82**, causing the chamber to have an increased thickness **308-2**. In FIG. **21**B, the fluid-filled chamber has a second thickness **308-2** that is associated with a maximum spherical optical power (e.g., +6.5 Diopters).

[0168] The range in spherical optical power provided by tunable lens **72-2** may be at least 10Diopter, at least 15 Diopter, at least 17 Diopter, etc. The total change in thickness between the minimum thickness of chamber **82** (in FIG.

21A) and the maximum thickness of chamber **82** (in FIG. 21B) may be at least 0.5 millimeters, at least 1.0 millimeters, at least 1.2 millimeters, etc.

[0169] Adjusting the thickness of chamber **82** may adjust the spherical optical power provided by tunable lens **72-2**. To adjust the cylindrical optical power provided by the lens module, an additional lens element **310** may optionally be included between lens element **120** and viewer **102**. Instead or in addition, the optical module may include one or more computer-controlled positioners that are configured to rotate lens element **126** relative to lens element **120**. In the example of FIGS. **21**A and **21**B, a first computer-controlled positioner **312-1** is coupled to lens element **120** and is configured to rotate lens element **120** within the YX-plane whereas a second computer-controlled positioner **312-2** is coupled to lens element **126** and is configured to rotate lens element **126** within the YX-plane. Rotating lens elements **120** and **126** relative to one another may adjust the total cylindrical optical power provided by lens module **72**.

[0170] In another possible arrangement, shown in FIG. **22**, the shape and/or position of partially reflective layer **128** is adjusted to change the spherical and/or cylindrical optical power provided by the lens module. In the example of FIG. **22**, lens module **72** includes a lens element **126** and a lens element **120**. Lens element **126** has a convex surface facing display **18** and a concave surface facing viewer **102**. Lens element **120** has a convex surface facing display **18** and a concave surface facing viewer **102**. Partially reflective layer **128** is attached to the concave surface of lens element **126**. Reflective polarizer **122** is attached to the concave surface of lens element **120**. Quarter wave plate **124** is depicted as being attached to partially reflective layer **128** at the concave side of lens element **126**. This example is merely illustrative. Quarter wave plate **124** may optionally be attached to the convex surface of lens element **120** or the concave surface of lens element **120** if desired.

[0171] As shown in FIG. **22**, lens element **126** may be attached to a computer-controlled positioner **312**. The computer-controlled positioner **312** may adjust the size of a gap **314** between QWP **124**/partially reflective layer **128**/lens element **126** and lens element **120**. In other words, computer-controlled positioner **312** may shift the position of partially reflective layer **128** along the Z-direction to adjust the spherical optical power provided by lens module **72**. Computer-controlled positioner **312** may shift the partially reflective layer laterally without adjusting the curvature of the partially reflective layer.

[0172] Instead or in addition to adjusting the lateral position of partially reflective layer **128**, one or more actuators **90** may be positioned around the periphery of the partially reflective layer **128** to adjust a curvature of partially reflective layer **128**. Similar to as shown and discussed in connection with the tunable lens in FIGS. **4** and **5**, the actuators may selectively bias partially reflective layer **128** and/or lens clement **126** at one or more points along the periphery of the reflective layer **128** and/or lens element **126** in order to selectively bend the reflective layer **128** and lens element **126**. Selectively bending the partially reflective layer may adjust the direction of an axis of cylindrical optical power and/or a magnitude of the cylindrical optical power.

[0173] In one illustrative arrangement, lens clement **126** in FIG. **22** is a semi-rigid lens element formed from polycarbonate. In general, each one of the lens elements in FIGS. **6-22** may be elastomeric, semi-rigid, or rigid.

[0174] In the example of FIG. **22**, the gap between lens element **120** and wave plate **124** may be air-filled or may be filled with a low-index filler.

[0175] FIG. **23** is a flowchart of an illustrative method of operating a head-mounted device **10** with a tunable lens (e.g., any of the tunable lenses of FIGS. **6-22**). At step **202**, the head-mounted device may gather data. The data may be gathered from external equipment **60**, from one or more sensors in device **10**, from one or more output devices in device **10**, etc.

[0176] Head-mounted device **10** may wirelessly receive information from external equipment **60** at step **202**. The information received from external equipment may, for example, indicate if the user is actively viewing the external equipment and/or a distance between the external equipment and the head-mounted device. The information received may include raw data (e.g., accelerometer data indicating a raise-to-wake gesture) and/or a notification that the external equipment is being actively viewed (without necessarily including raw data). External equipment **60** may estimate the distance between head-mounted device **10** and the external equipment using ultra-wideband (UWB) communications and/or depth sensing (e.g., using a LIDAR sensor in the external equipment).

[0177] Head-mounted device **10** may gather data from one or more sensors at step **202**. The sensors used to gather data at step **202** may include inward-facing camera **22**, outward-facing camera **24**, microphone **26**, position and motion sensors **28**, ambient light sensor **30**, magnetometer **32**, heart rate monitor **34**, depth sensor **36**, temperature sensor **38**, touch sensor **40**, moisture sensor **42**, gas sensor **44**, barometer **46**, gaze-tracking sensor **48**, button **50**, light-based proximity sensor **52**, GPS sensor **54**, etc.

[0178] Head-mounted device **10** may gather data associated with one or more output devices at step **202**. The data associated with an output device may include information on whether or not that output device is powered on and/or the type of content being presented if the output device is powered on. For example, the data gathered at step **202** may include information on whether display **18** in head-mounted device **10** is operating and what type of content is being presented on display **18** (e.g., the depth of content presented by display **18**). The depth of content presented by display **18** may be adjusted by changing the virtual image distance (VID) (e.g., through optics, light field, etc.) and/or by rendering a difference in binocular disparity while keeping the VID the same. The content may be in a plane or three-dimensions, may have multiple depths, and may be of a variety of types including text, UI, graphics, etc.

[0179] The data gathered at step **202** may additionally include information on the number and/or type of applications installed on head-mounted device **10**, the number and/or type of applications currently running on head-mounted device **10**, information from an application running on head-mounted device **10**, etc. Depending on the type of application or the content of the application, the tunable lens may be adjusted to any preferred settings.

[0180] The data gathered at step **202** may include any other desired information (e.g., the time of day, the length of time the head-mounted device **10** has been operated, calendar information for the user of the head-mounted device, etc.).

[0181] Gathering data at step **202** may further include monitoring one or more additional components of head-mounted device **10**. For example, information from one or more passthrough cameras, one or more adjustable tint layers and/or adjustable transparency layers, one or more speakers, etc. may be monitored at step **202**. Any adjustments to one of these components (e.g., an adjustment to an operating setting of the passthrough camera, an adjustment to the transparency of an adjustable transparency layer, etc.) may be gathered at step **202** and subsequently used to update the tunable lens and/or other system components.

[0182] In general, any of these types of data may influence adjustments of tunable lens **72-2**.

[0183] Next, at step **204**, head-mounted device **10** may adjust the tunable lens (e.g., tunable lens **72-2** based on the gathered data). Adjusting the tunable lens may include increasing the optical power provided by the tunable lens, decreasing the optical power provided by the tunable lens, changing the lens center from a first position to a second position within the plane of the lens, and/or any other desired adjustments to the tunable lens. The tunable lens may be adjusted to provide full prescription correction to the user wearing the head-mounted device (e.g., covering both spherical and cylindrical corrections).

[0184] Other components within head-mounted device **10** may be adjusted at step **204**. For example, the data gathered at step **202** may cause an update to a passthrough camera, an adjustable tint layer, an adjustable transparency layer, a speaker, or any other desired component within head-mounted device **10**.

[0185] As a specific example, gaze-tracking sensor **48** may be used to determine a user's gaze direction at step **202**. The user's gaze direction may indicate where in the physical environment the user is focused (e.g., at a relatively close distance or at a relatively far distance) and the tunable lens may be updated accordingly at step **204**.

[0186] As another example, gaze-tracking sensor **48** may be used to determine the position of the center of the user's eye at step **202**. The position of the user's eye (e.g., the user's pupil center) may be used to adjust the tunable lens at step **204** to compensate for geometric distortion associated with one or more lenses in optical module **70** or any other optical artifacts (e.g., chromatic aberrations, non-uniformities, vignetting).

[0187] As another example, gaze-tracking sensor **48** may be used to determine the vergence of the user's eye at step **202**. The vergence of the user's eye may be used to adjust the tunable lens at step **204** to compensate for the user's presbyopia, prism correction, etc. The vergence signal may also feed into the rendered content depth by either adjusting the binocular disparity or VID if there is any displayed content.

[0188] As another example, one or more sensors or input components in device **10** may be used to identify the user operating device **10**. The user operating device **10** may be identified using the gaze-tracking sensor, a fingerprint sensor, and/or any other desired sensors within device **10**. Instead or in addition, the user operating device **10** may be assumed to be a user associated with an account that is logged in on device **10**. The user may have a known preferred state for the tunable lens. Accordingly, the identity of the user operating the device may be used to adjust the tunable lens at step **204** (e.g., to place the tunable lens in the known preferred state for that user).

[0189] As another example, at step **202** control circuitry **14** may receive information regarding the depth of the content that is presented by display **18**. When the depth of the content on display **18** is relatively short, the user may be assumed to be focused at a relatively short depth. When the depth of the content on display **18** is relatively long, the user may be assumed to be focused at a relatively long depth. At step **204** the tunable lens may be updated based on the depth of the content on display **18**.

[0190] In general, any of the eye tracked signals may change the state of the tunable lens to improve acuity and comfort. As examples, the vergence signal, with or without any displayed content may be used to drive the tunable lens to a state so the user can see the real world clearly either directly in an AR system or through a combination of passthrough camera and display focus adjustments.

[0191] The foregoing is merely illustrative and various modifications can be made to the described embodiments. The foregoing embodiments may be implemented individually or in any combination.

What is claimed is:

1. An electronic device, comprising:
- a head-mounted support structure; and
- an optical module coupled to the head-mounted support structure, wherein the optical module comprises:
  - a waveguide having first and second opposing sides;
  - a display that is configured to emit light into the waveguide;
  - a negative bias lens on the first side of the waveguide; and
  - an adjustable positive bias lens on the second side of the waveguide.

2. The electronic device defined in claim **1**, wherein the negative bias lens is a non-adjustable negative bias lens.

3. The electronic device defined in claim **1**, wherein the negative bias lens is an adjustable negative bias lens.

4. The electronic device defined in claim **3**, wherein the adjustable positive bias lens and the adjustable negative bias lens are adjusted independently.

5. The electronic device defined in claim **3**, wherein the adjustable positive bias lens and the adjustable negative bias lens are adjusted synchronously.

6. The electronic device defined in claim **3**, wherein the adjustable negative bias lens comprises a tunable lens element with a fluid-filled chamber.

7. The electronic device defined in claim **6**, wherein the adjustable negative bias lens further comprises a non-adjustable lens element with a surface having concave curvature.

8. The electronic device defined in claim **1**, wherein the optical module further comprises a cover layer that is in direct contact with the adjustable positive bias lens.

9. The electronic device defined in claim **1**, wherein the optical module further comprises a cover layer that is separated from the adjustable positive bias lens by an air gap.

10. The electronic device defined in claim **1**, wherein the optical module further comprises:
- an input coupler that couples the light from the display into the waveguide; and
- an output coupler that couples the light from the display out of the waveguide.

11. The electronic device defined in claim **1**, wherein the negative bias lens comprises third and fourth opposing sides, wherein the third side is interposed between the waveguide and the fourth side, and wherein the fourth side has a surface with concave curvature.

12. The electronic device defined in claim **1**, wherein the adjustable positive bias lens comprises a fluid-filled chamber.

13. The electronic device defined in claim **1**, further comprising:

a gaze-tracking sensor, wherein the adjustable positive bias lens is configured to be adjusted based on a vergence detected by the gaze-tracking sensor.

14. The electronic device defined in claim **1**, further comprising:

a gaze-tracking sensor, wherein the adjustable positive bias lens is configured to be adjusted based on an eye position detected by the gaze-tracking sensor.

15. The electronic device defined in claim **1**, wherein the adjustable positive bias lens is configured to be adjusted based on a depth of content presented by the display.

16. The electronic device defined in claim **1**, further comprising:

a gaze-tracking sensor, wherein the adjustable positive bias lens is configured to be adjusted based on a gaze direction detected by the gaze-tracking sensor.

17. An electronic device, comprising:

a head-mounted support structure; and

an optical module coupled to the head-mounted support structure, wherein the optical module comprises:

a display;

a partially reflective layer;

a tunable lens element; and

a reflective layer with a surface having concave curvature.

18. The electronic device defined in claim **17**, wherein the display is configured to emit light that passes through the tunable lens element and the partially reflective layer, then is reflected by the reflective layer towards the partially reflective layer, and then is reflected by the partially reflective layer towards an eye-box and wherein light from a physical environment is configured to pass through the partially reflective layer towards the eye-box.

19. An electronic device, comprising:

a head-mounted support structure; and

an optical module coupled to the head-mounted support structure, wherein the optical module comprises:

a display;

a partially reflective layer; and

a tunable lens element that is interposed between the display and the partially reflective layer.

20. The electronic device defined in claim **19**. wherein the display is configured to emit light that passes through the tunable lens clement and is then reflected by the partially reflective layer towards an eye-box and wherein light from a physical environment is configured to pass through the partially reflective layer towards the eye-box.

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